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CONTROLLING SULFIDES IN SANITARY SEWERS USING AIR AND OXYGEN

City of Port Arthur

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By

R. Joe Sewell

City of Port Arthur
Port Arthur, Texas 77640

Project No. 11010 DYO
Program Element No. 1BB043

Project Officers

Charles L. Swanson and John N. English*
*Advanced Waste Treatment Research Laboratory
National Environmental Research Center
Cincinnati, Ohio 45268

NATIONAL ENVIRONMENTAL RESEARCH CENTER
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

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FOREWORD

Man and his environment must be protected from the adverse effects of pesticides, radiation, noise and other forms of pollution, and the unwise management of solid waste. Efforts to protect the environment require a focus that recognizes the interplay between the components of our physical environment--air, water, and land. The National Environmental Research Centers provide this multidisciplinary focus through programs engaged in

- studies on the effects of environmental contaminants on man and the biosphere, and
- a search for ways to prevent contamination and to recycle valuable resources.

As part of these activities, the study described here investigated the applicability of using air and pure oxygen entrainment devices to control sulfides in sanitary sewers.

A. W. Breidenbach, Ph.D.
Director
National Environmental
Research Center, Cincinnati

ABSTRACT

This report documents ambient sulfide conditions and corrosion rates in a sanitary sewerage system, and presents the results of a study that demonstrated that the use of air or pure oxygen were effective in controlling sulfides. The three techniques used to entrain the gases in the sewage included injection, U-tubes, and pressure tanks.

Sulfide control was evaluated at eight separate locations involving lift stations, force mains, and receiving gravity lines. The entrainment techniques studied were not optimized. However, odor and corrosion problems were abated. Preliminary cost data indicated that air injection into force mains, and the use of air with the U-tube were the least costly sulfide control measures.

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SECTION I

CONCLUSIONS

1. Injection of air or pure oxygen into force mains reduced sulfide concentrations to acceptable levels. A minimum feed rate for these sources of oxygen was found to exist for the reduction of existing sulfides and prevention of further generation. The cost of air injection was less than pure oxygen for the conditions of the study. The ability to obtain a dissolved oxygen residual with air injection was not demonstrated and the amount transferable using pure oxygen appeared to be limited.

2. The U-Tube proved effective in the control of sulfides for the air: water ratios evaluated. Reductions of sulfide in the U-Tube were equal to other systems tested, and sufficient oxygen was entrained to permit continued oxidation in downstream gravity sewers.

3. The pressure tank as a means of controlling sulfides was demonstrated; however, the applied oxygen required under operational conditions was excessive. For the conditions of the study, this was the most costly method of sulfide control.

4. The net effect of the aeration program was the reduction of sulfide levels downstream of control points. Further, the severe odor problems at various locations have been eliminated and have been reported only during periods where control equipment was inoperative.

5. At the control points of the study, the recirculation of aerated sewage to the wet well proved to be effective in the reduction of sulfides in the wet well and reduced odor problems.

6. The force main proved to be the major generator of sulfides in the system. The sewage transfer station was shown to be an effective point at which existing sulfides can be controlled using oxygen and the oxygen serves to prevent additional sulfide generation in force mains.

SECTION II

RECOMMENDATIONS

The use of air or pure oxygen for sulfide control should be considered both in the design of new systems and for existing systems. The sewage transfer station can be an effective point of control with optional methods of injection available for economic evaluation. There are several factors which must be considered in designing control systems. These include: (1) physical configuration of the system; (2) sewage characteristics; and (3) the ability to conduct field studies.

The first step is to identify the physical configuration and constraints. These include the force main gradient, length and diameter. Equally important is pumping capacity and available heads. Changes in grade, depressions or other restrictions can prevent the system from functioning. The choice of equipment for oxygen injection will be governed by these parameters.

Sewage characteristics that are significant include temperature, biochemical oxygen demand and sulfide levels of incoming sewage. The immediate dissolved oxygen demand of the incoming sewage can provide information on the magnitude of oxygen required.

Design parameters should consider the oxygen application in mg/l in lieu of air:water ratios, or in air feed rates expressed as a function of force main diameter. The applied oxygen in this manner relates oxygen demand of the sewage to system hydraulics.

The field testing of air injection should be performed in addition to testing for sewage characteristics. This can be accomplished by the use of a mobile air compressor with a self contained power supply. A necessary requirement is a flow measuring device capable of measuring anticipated flow rates. In addition to this, discharge pump pressures should be monitored and flow measurements made or estimated. The performance of these preliminary evaluations will assist in the decisions that must be made.

SECTION III

INTRODUCTION

In 1967 the City of Port Arthur, Texas, following recommendations from its Water and Sewer Study Committee, initiated studies dealing with the deterioration of the City's concrete sanitary sewer lines. These studies revealed that the sewerage system was under serious attack by hydrogen sulfide corrosion. After careful consideration of the various recommendations for bringing the deterioration under control, the control method recommended by the Committee was the injection of air and/or pure oxygen into the principal force mains identified in the preliminary evaluations.

The City implemented the control methods recommended by the Committee at three locations in December, 1968. On March 25, 1969 the City of Port Arthur accepted a Demonstration Grant from the Environmental Protection Agency to expand the work to additional locations in the sewerage system. A supplemental grant was awarded on June 24, 1970 to install and evaluate other control measures including U-tube aerators at two lift stations.

PURPOSE AND SCOPE

The purpose of the study was to demonstrate and evaluate the effectiveness of oxygen in controlling hydrogen sulfide in sanitary sewerage systems. The oxygen sources utilized were air and pure oxygen. Various methods of entrainment were also evaluated.

The scope of the project was extensive in that its goal was to place the entire sewage collection system under the proposed methods of hydrogen sulfide control, thereby affording protection to the entire system. An ancillary function of the study was to ascertain what effects the entrainment of oxygen, at levels required for hydrogen sulfide control, had on sewage characteristics.

The demonstration project consisted of two separate phases; the initial grant award, Phase I; and the supplemental grant, Phase II. The first Phase of the study consisted of the evaluation of hydrogen sulfide control measures at four locations (Railroad Avenue-Thomas Boulevard Pump Station, Grannis Avenue Pump Station, Smith-Young Pump Station, and 19th Street-Stillwell Boulevard Life Station). Each station and its respective control measure is an integral part of a system, and thus will be discussed as a part of that system. A system is here defined as the lift station(s), force main(s), and receiving gravity lines which form a specific physically related unit. The physical nature of the system was an important consideration in the selection of control methods to be evaluated in the system.

Control measures were evaluated at four additional stations during the second phase of the project. Two of the additional stations, the Pear Ridge (abandoned sewage treatment plant) Lift Station and Pioneer Park (Hospital) Lift Station, are part of the Pear Ridge System. The remaining two stations, Lake Charles Lift Station and Mainline Pump Station, are located on the major interceptor that parallels the Sabine-Neches Ship Channel. The wet well of the Lake Charles Lift Station receives sewage from the Lakeshore and Stillwell Systems. The Mainline Station, which is the final pump station in the City's collection and transmission system, receives sewage from all systems within the central portion of the city.

HISTORY

The City of Port Arthur began construction of its sanitary sewerage system in 1910 with construction of the main sewage treatment facilities in 1959. Since its initial construction, the system has continually been extended to provide service to unsewered areas as well as meeting the population growth of the contiguous areas. In addition, the City of Port Arthur has effectuated, to a limited extent, regionalization of sewage treatment. The City has contracted with neighboring cities to treat their sewage, thereby eliminating smaller treatment plants serving these communities.

The City of Port Arthur has experienced all of the problems associated with hydrogen sulfide gas in sewerage systems. The most severe was the loss of life of two workmen at the sewage treatment plant in 1962. The cause of death was attributed in part to hydrogen sulfide gas (1).

By 1967, the city had experienced numerous structural failures in the sanitary sewer system in the form of cave-ins (2). The structural failures were associated with the reduction of the load carrying capacity of the pipe, which in turn was caused by the deterioration of the pipe wall by the attack of sulfuric acid. Sulfuric acid is one of the oxidation products in the hydrogen sulfide cycle evidenced in sanitary sewage collection systems.

Odor problems have been reported throughout the city with varying degrees of intensity. Two methods have been employed to control odor, venting and masking. Venting has been tried in Port Arthur with only limited success. Masking does not really solve the odor problem, but merely substitutes a new odor. This method is only partially successful and is very expensive.

Major hydrogen sulfide corrosion problems have also occurred above ground. This is prominently evidenced by the corrosion of equipment at the sewage treatment plant, which is directly related to the release of hydrogen sulfide gas from the raw sewage. At one location in the city, where serious odor problems and structural failures have been reported, galvanized chain link fences have been reduced to a series of rusty wires by the gas.

The construction of sanitary sewage collection systems represents a significant capital investment to a city, and due to their character are normally designed for a fifty year period. One of the common forms of financing these systems is by selling bonds with a maturation date of thirty years. There are documented instances in Port Arthur of failure of sanitary sewers within six years after construction, leaving twenty-four years of bonded indebtedness for facilities that no longer exist. Equally important is the additional economic burden imposed by replacement costs which are considerably greater than initial construction costs due to surface improvements and inflation.

During the summer of 1967, based upon recommendations by the Water and Sewer Study Committee, the City Council authorized a television survey of selected sanitary sewer lines in the city. This survey demonstrated extensive damage to the major trunk lines which was attributed to hydrogen sulfide corrosion. At that time it was estimated that the annual loss due to this corrosion was $600,000 per year or $10 per capita. Based on 1967 material and construction prices, replacement of these lines would cost approximately ten million dollars (3). This loss could be prevented if the deterioration could be brought under control. Thus, the City Council authorized additional studies to isolate the principle points of hydrogen sulfide generation within the system and to evaluate various methods of hydrogen sulfide control. This work led to the subject study as reported herein.

SULFIDE GENERATION AND CONTROL

Corrosion problems encountered in sanitary sewers are generally attributable to the presence of hydrogen sulfide. Since hydrogen sulfide is intimately associated with the problems, it is apropos to review the properties of hydrogen sulfide. Hydrogen sulfide is a colorless gas with a foul odor (rotten eggs); is slightly heavier than air; is moderately soluble in water; and small amounts in air cause headaches while higher concentrations cause paralysis in the nerve centers of the heart and lungs which results in fainting and death (4). Further, concentrations of the gas of 0.2 percent are toxic to humans after a few minutes exposure (5). Another significant property of hydrogen sulfide is that it is explosive at concentrations of 4.3 percent (6). Hydrogen sulfide is soluble in water to the extent of 3000 to 4000 mg/l at the normal temperatures found in sewers (7). The corrosion potential of sulfuric acid, the oxidation product of hydrogen sulfide, will be discussed later in this report.

The properties of hydrogen sulfide noted above clearly indicate the concern over the presence of this gas in a sanitary sewerage system. It is intuitively obvious that sewers are not designed to generate hydrogen sulfide gas, rather the gases are generated as a function of the environment of the sanitary sewer and the material transported. Germane to the discussion is the consideration for the potential of hydrogen sulfide generation in sanitary sewers.

Potential for Hydrogen Sulfide Generation

A widely accepted theory that describes the presence of hydrogen sulfide in sanitary sewers is its generation from sulfate-reducing bacteria which use the sulfates as their hydrogen acceptor. The reaction is abbreviated in symbolic form as follows where C is used to designate organic matter:

$$SO_4^{=} + 2C + 2H_2O \xrightarrow{\text{bacteria}} 2HCO_3^{-} + H_2S$$

$$S^{=} + 2H^{+} \rightleftharpoons H_2S$$

The sulfate-reducing bacteria associated with this reaction are classified as obligate anaerobes (8). "One of the most interesting aspects of the sulfate-reducing bacteria is the highly specific character of these bacteria, especially in view of the fact that most of the common bacteria reduce sulfates to sulfide in their protoplasm" (8). The significance of the presence of sulfate on sulfide generation in sanitary sewers is therefore apparent. In many instances, where natural occurring sulfates are of minor concentrations they are added to the water supply when it is chemically treated by the use of a coagulation aid such as alum. It has been reported in other studies that when sulfates in the sewage are below a concentration of 25 mg/l, the generation of sulfides is inhibited under certain conditions (6). This would imply that sulfide generation is almost assured when concentrations are in excess of a limiting value. Pomeroy and Bowlus have, however, referenced areas in Southern California where sulfates ranged from 200 to 400 ppm yet sulfides were not generated in sanitary sewers. They also pointed out that areas in Southern California and Arizona have experienced sulfide problems with low sulfate concentrations (9).

Neel, in work in southeast Texas, reported that significant hydrogen sulfide has been generated from sewage where the carrier water of the waste had an initial sulfate concentration of less than three milligrams per liter (10).

Sulfur in sewage occurs in two forms, organic and inorganic (11). Sulfate ions represent the major portion of inorganic sulfur and as indicated, occur in varying amounts in carrier water. Organic sulfur in sewage has been reported to be low and in the magnitude of 0.2ppm (12). A value of 1-2 ppm (of sulfur) has also been reported for domestic sewage, reaching 5-10 ppm in industrial wastes (13). There are many organic compounds that contain sulfur with protein being one readily recognized. The elementary composition of all proteins contains approximately 0.2 percent sulfur (14).

The generation of hydrogen sulfide can result from the reduction of organic sulfur, inorganic sulfur or combinations thereof depending upon concentrations (13). Further, it has been pointed out in other studies that it is feasible for hydrogen sulfide production from organic sulfur compounds to precede its production from sulfates in sewage that contains both sources of sulfur (15). Thus, it is obvious that sanitary sewage, regardless of the quality of the carrier water, does have an inherent potential for the generation of hydrogen sulfide. This potential will continue until such time that all sulfate and other sulfur bearing compounds have been completely reduced.

Sewage strength, or the concentration of the biological nutrients present, is a measure of sulfide generating potential. The greater the sewage strength or amount of organic matter infers a higher concentration of sulfur with the potential for reduction to sulfides. The most common measure of sewage strength is the BOD (Biochemical Oxygen Demand) Test. Therefore, the greater the BOD the higher the sulfide potential.

The potential for hydrogen sulfide generation, based upon presence of sulfur bearing compounds, exists universally in sanitary sewers. However, this potential for sulfide generation fails to explain the condition whereby sulfides and hydrogen sulfide are found in large quantities in some sewers while appearing in only trace amounts in others. It soon became apparent that while the sulfur compounds provide the potential for conversion to sulfides, other factors control the generation of the gas. This has been the subject of several studies, which have contributed to the fundamental understanding of sulfide generation, the principal factors affecting generation and subsequent control of the generation.

Factors Effecting Hydrogen Sulfide Generation

The location or point within the sanitary sewer where the gas is generated must be determined before control measures can be considered. Pomeroy and Bowlus (9) reported that "In free flowing sewers, sulfides are produced only by slimes on the submerged surface of the sewer and by deposited sludge." This was not validated by later studies; however, the slimes remain the primary generator of sulfides in gravity sewers (21).

In gravity lines, the slime develops in the invert and sides which are inudated at all flows. It therefore follows that the magnitude of the sulfide generation is a function of the active area of contact. Unlike the gravity sewer, the total inside surface area of force mains is covered with an active biological mass.

The factors that control the magnitude of sulfide generation are strength of sewage, temperature, retention time or velocity-length function, and a surface area factor. Under normal conditions, there is no opportunity for aeration in force mains and the sulfide generation continues. Thus the force main has proven itself as a major sulfide generator. This fact has been reported in studies performed in the Gulf Coast Plain of Texas (6) (23).

Studies have indicated the significance of temperature on sulfide generation. In these studies the rate of generation was found to increase about 7 percent per degree rise of temperature up to 30° Centigrade (16). The rates of generation at 30° and 37° were similar, indicating a possible optimum in that range. There exists a minimum temperature, regardless of other conditions, for which sulfides will not be generated.

The first published work relating sulfide buildup to sewage strength (BOD) and velocity of flow also included temperature effects. The temperature for the Standard BOD is 20° Centigrade. For any other temperature it is corrected by a factor based on the condition that biological activity increases (geometrically) seven percent per degree change in temperature from the standard. This is based upon work by Baumgartner in 1934 (16).

The formula for converting a Standard BOD to the effective BOD at any temperature is given by the following:

$$\text{Effective B.O.D.} = \text{Standard B.O.D.} \times (1.07)^{t-20} \qquad [1]$$

Using this formula data was presented in 1946 (9) relating the Effective B.O.D. to the velocity required to prevent sulfide build-up. This data may be expressed in equation form as follows:

$$\text{Marginal E BOD} = 55V^2 \qquad [2]$$

in which V is the velocity in feet per second and is applicable only where flow is not greater than one half full. If the actual velocity is below that given, sulfide buildup could be expected (9).

Use of the equation and table for the prediction of sulfide build-up requires the following data to be used:

a) peak summer temperatures
b) daily peak BOD values
c) maximum effective BOD calculated
d) actual velocity during these peak flow conditions is also determined.

The pH (negative log of the hydrogen ion concentration) of the sewage is also a factor affecting hydrogen sulfide generation. However, Pomeroy once stated "pH is not likely to have much effect on the rate of generation in sewers within the range from 6 up to 8 or perhaps 9 (9)." Perhaps a more significant affect of pH on sulfide in sewers than that of generation is the form in which it occurs, i.e. sulfide ion ($S^=$), hydrosulfide ion (HS^-) or un-ionized hydrogen sulfide (H_2S). The insoluble portion of sulfides is of no concern as these are not available to be released as a gas. The dissolved sulfide is the form from which the gas develops. At a pH=6, 83 percent of the dissolved sulfide is un-ionized while at a pH=7, 33 percent is un-ionized. Concentration greater than a pH=8 becomes insignificant as only 4.8 percent is un-ionized (24) (25). Thus, the lower the pH, the greater the potential for evolution of the gas to the sewer atmosphere.

The retention or residence time of the sewage, sometimes referred to as sewage age, in the collection system is often alluded to as a contributing factor in sulfide buildup. Again reference is made to the work of Pomeroy and Bowlus in which they state, "Actually the age of the sewage is of minor importance. It is not the age that matters; It is how rapidly the sewage flows" (9). This is further explained by the following, "The rate at which sewage flows through a sewer does not affect the rate of output of sulfide by the slimes on the sides of the sewer, until velocities are reached which scour the sides and which keep the stream in a well-aerated condition. This scouring effect is probably not of much consequence until the velocity exceeds 3 feet per second" (9). This is applicable only to free flowing sewers.

One additional factor related to velocity is the effect it has upon absorption of oxygen. Research reported by Streeter et al, indicated that the rate of absorption of oxygen by a free surface stream varies in proportion with the 1.75 exponent of the velocity (17). Additional work on this subject was done by Kehr in 1938 (18). This clarifies the previous conditions whereby the generation of sulfides is limited in the flowing portion of a sewer. The reaeration would inhibit the growth of strict anaerobes while at the same time oxidize the sulfides released by facultative organisms.

The above referenced material, although explaining the transfer of oxygen across a liquid-gas interface, does not directly relate to the condition found in sanitary sewers. Recent research performed on aeration rates in sewers provides more specific information on the subject. More important than providing a mystical number to be erroneously used as a panacea, the research provides an equation for predicting the exchange coefficient for specific conditions (19) (7). This work has provided the subject of hydrogen sulfide control with a new tool for future use that should result in more rational designs.

Research has continued to pursue the generation of sulfide in both gravity lines and force mains, with the biochemical oxygen demand, temperature, velocity and pipe geometry the principal factors evaluated. In 1950, Davy presented work in which the Pomeroy and Bowles relationships between BOD, temperature and velocity had been tested for local conditions as found in Melbourne, Australia (22). This work oriented sulfide production to being a function of velocity. The work by Davy was later modified by Pomeroy for gravity sewers resulting in more simplified equations for predicting sulfide buildup (21).

Mechanisms of Hydrogen Sulfide Corrosion

Hydrogen sulfide will ionize in water to form a weak diprotic acid, hydrosulfuric acid, which yields hydrogen and hydrogen sulfide ions. The hydrosulfide ion will then ionize to form hydrogen and sulfide ions (4). This would represent one form of acid formation on the crown and walls of the pipe. There is one other form of acid formation associated with the hydrogen sulfide that is generally recognized to be the predominant form as found in sanitary sewers. This is the oxidation of hydrogen sulfide to sulfuric acid by aerobic bacteria. Sulfuric acid is a strong acid whereas hydrosulfuric acid is a weak one. Sulfuric acid, being more reactive, explains more clearly the reduction of the cement binder (insoluble in water) to water soluble salts, primarily sulfates (26) (13). The complete cycle with chemical equations is shown in Figure 1. The uniqueness of the cycle is the role played by oxygen (27).

Therefore, it is not the hydrogen **sulfide** gas, but rather sulfuric acid, the product of the oxidation of the gas, which attacks the concrete sewer pipe. After being generated, primarily in the slimes, the sulfides and gas enter the flowing sewage. The gas that is not oxidized may then be released to the sewer atmosphere. The release of the gas in gravity lines occurs primarily at points of turbulence such as improperly constructed joints, manholes, etc. Large amounts of the gas are released at wet wells where the inflow line is not submerged. The turbulence at the discharge point of the force mains is another major point of release of the gas.

The humidity of the sanitary sewer atmosphere is very high and the exposed walls of the pipe are normally moist with water of condensation. This water serves as a receiver of the liberated hydrogen sulfide gas and provides a harbour for bacteria. Ventilation of the sewer permits oxygen to enter the sewer which is also absorbed by the moisture. The oxygen permits the bacteria that develop to be aerobic. It is at this stage that another facet of the uniqueness of the hydrogen sulfide generation process in a sewer is manifested. Although the gas is initially generated under anaerobic conditions, an aerobic environment is required for the final oxidation to sulfuric acid.

Control of Hydrogen Sulfide

The significance of hydrogen sulfide in sanitary sewer systems has been stated and the need for control of the gas identified. Researchers have essentially two basic approaches to control hydrogen sulfide. The first approach employs methods which prevent generation while the second permits the generation to occur with the subsequent rendering of the gas harmless by chemical reactions. Prior to any discussion of specific techniques employed and reported, a review of the most significant factors involved, i.e. basic properties, and how they can give insight into control techniques is appropriate.

Bacterial Action - - Bacterial action as found in gravity sewers is the first factor to be reviewed as it is applicable to control of sulfides from either inorganic (sulfate ion) or organic sources of sulfur. In the former, the attack of the sulfate ions is by strict anaerobes that utilize the combined oxygen and the sulfur becomes a hydrogen acceptor. This alludes to several methods of control. First, an alternate combined oxygen source could be provided that would be more readily available to the bacteria. Secondly, the maintenance of a residual dissolved oxygen

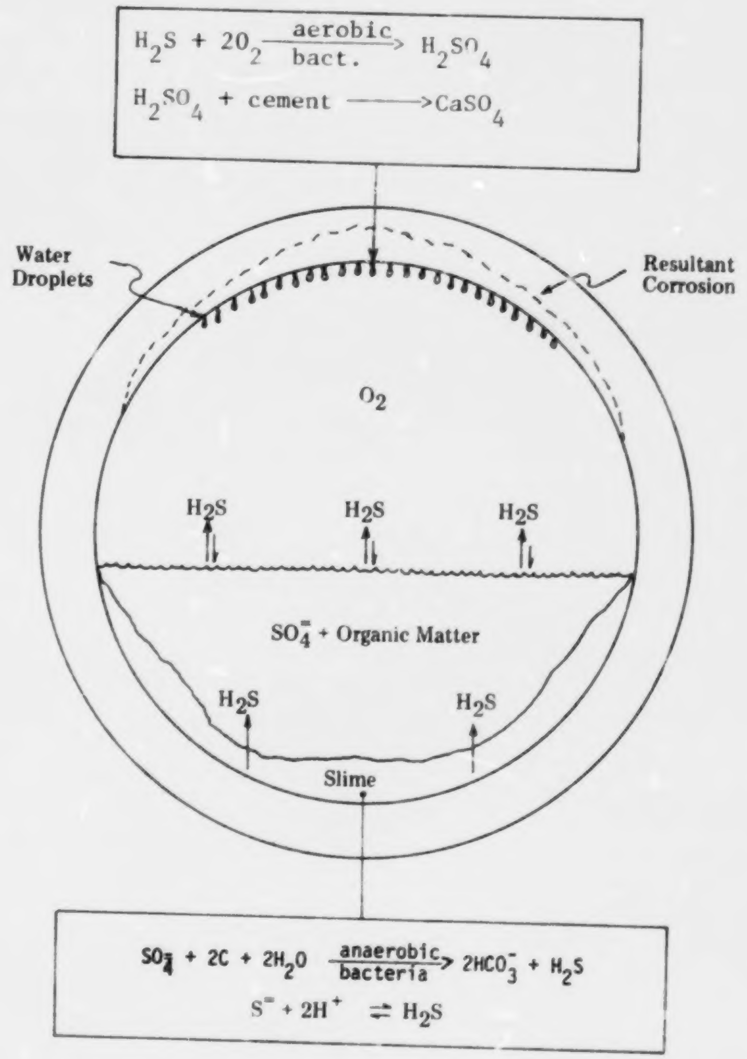

$H_2S + 2O_2 \xrightarrow[\text{bact.}]{\text{aerobic}} H_2SO_4$
$H_2SO_4 + \text{cement} \longrightarrow CaSO_4$
Water Droplets
Resultant Corrosion
O_2
H_2S
H_2S
H_2S
$SO_4^{=}$ + Organic Matter
H_2S
H_2S
Slime
$SO_4^{=} + 2C + 2H_2O \xrightarrow[\text{bacteria}]{\text{anaerobic}} 2HCO_3^{-} + H_2S$
$S^{=} + 2H^{+} \rightleftharpoons H_2S$

Figure 1. Hydrogen Sulfide Development in a Sanitary Sewer

would restrict the growth of obligate anaerobic bacteria as well as oxidize the sulfides released by facultative bacteria. Free oxygen has the same effect on anaerobic bacteria as that achieved by injecting a toxic material. The use of toxic materials serves as an additional method of control.

Organic compounds containing sulfur present an entirely different problem. The common bacteria that utilize organic matter are responsible. These organisms secrete sulfides from the breakdown or organic compounds while undergoing aerobic metabolism. If the dissolved oxygen is depleted, they will seek a combined oxygen source. If the combined oxygen source should be sulfates, the magnitude of sulfides released would be increased. One method of control would be to take steps to assure the presence of oxygen to oxidize sulfides released to the environment. A second method, under anaerobic conditions would be the provision of an alternate combined oxygen source, such as nitrates, in lieu of sulfates. The addition of toxic chemicals to kill the bacteria would be an alternative method of biological control.

Chemical Action -- There are several ramifications to the use of chemicals. Under the discussion of bacterial action, the use of toxic chemicals represents one form of control. Second, is the addition of chemicals to provide an alternate combined oxygen source as previously discussed. Provided the sulfides have already been produced, these could be precipitated by addition of heavy metals that form insoluble metallic sulfides. The adjustment of pH to either extreme, i.e. acid or base, will inactivate the [illegible] layer. The addition of chemicals, for example chlorine, would oxidize the sulfides in lieu of forming insoluble metallic salts. The addition of oxygen would also serve to oxidize any ionized sulfides and facilitate the dual purpose of maintaining aerobic conditions.

Physical Controls -- Physical control of sulfides could be accomplished by designing the system for velocities equal to or greater than the scour velocities. There are two types of scour involved and these should not be confused. A sediment scour velocity is one in which the inorganic material, such as sand that enters sewers, will be transported. This velocity has been reported to be from 1.6 to 2.0 feet per second (28). A slime scour velocity is one in which slimes are prevented from developing on the walls and invert of the pipe. There has been very little information reported on the magnitude of this velocity. One sewer which had a velocity of 4.9 feet per second was found to be relatively free of slime (29). This velocity would be expected to greatly exceed the sediment scour velocity and would not be practical.

A method applied in isolated instances has been flushing or dilution during low flows. In the latter, creek waters have been diverted to sanitary sewers to increase the flow and also provide additional dissolved oxygen (30) (31). Infiltration has provided the extra water in many instances. The advent of rigid water quality standards and the high cost of construction of sewage facilities has made these methods undesirable.

"Other methods to minimize odors and other sulfide nuisances are:

a) Minimize points of high turbulence within the system
b) Design pump station wet wells in a way which precludes the surcharge of tributary lines
c) Provide air jumpers across large siphons and around lift stations
d) Provide forced draft ventilation if there is a point where air may be depleted seriously of its oxygen content (7)."

The most frequently referenced methods of control that have been used are as follows:

Method	Action	References
Chlorination	destruction of sulfide	(9)(32)(38)(21)(34)(7)(35)
Nitrate (Sodium or Calcium)	alternate oxygen source	(9)(7)(21)(36)(37)
Iron Salts	precipitation of sulfides	(9)(7)(21)
Zinc Salts	precipitation of sulfides	(9)(7)(21)
Lime (Caustic Soda)	pH adjustment	(9)(7)(21)
Oxygen (Aeration)	oxidation	(9)(7)(38)(23)(39)(40)(41)(11)

Other methods that have been proposed and applied are directed primarily to the extension of useful life of the conduit and not control of the sulfides. There are two approaches to the problem, one is the use of sacrificial concrete and secondly the use of limestone aggregates (21). The major shortcomings of these methods, as in the case of using inert pipe materials, is that they do not control odor problems.

Hydrogen sulfide presents an odor problem that has brought about serious problems that have warranted control. The odor problems have varied from the sewerage system to the sewage treatment plant. Many of the plant odor problems result from sewage arriving at the plant with high levels of hydrogen sulfide. The treatment process releases these and creates nusiances. A comprehensive treatise of odor control at treatment plants was presented by Wisely (30)(31)(32). Most of the methods employed for odor control in sanitary sewers are the same as for sulfide control. Masking of odors by substitution has in some instances abated the odor problem; however this approach has two major shortcomings. First, the method is very expensive and second, the masking of the odor will not prevent corrosion.

SECTION IV

DESCRIPTION OF SEWERAGE SYSTEM

PORT ARTHUR, TEXAS

The City of Port Arthur, Jefferson County, Texas is located in the extreme southeast corner of the state approximately 90 miles east of Houston. With a maximum elevation of only 10 feet above sea level, the city is located within the flat, rolling terrain of the Gulf Coastal Plains.

The climate of the area may be best described as sub-tropical. This is evidenced by an annual mean temperature of 68.8° Fahrenheit, with the monthly mean temperature ranging from a high of 82.9° F in August to a low of 52.8° F in January.

The mean annual rainfall for the area is 52.38 inches. The rainfall is distributed fairly uniformly throughout the year, with July having the highest monthly mean rainfall, 6.32 inches, and March the lowest, 3.04 inches. The maximum rainfall of record for a month is 18.71 inches, while the minimum is zero.

The City of Port Arthur, with a 1970 population of 66,676, is a center for petroleum, petrochemicals, rice milling, and other industrial activities. One of the major activities is derived from the port facilities which are located on the intercoastal waterway. The proximity to the coast accounts for the extensive commercial fishing which serves the area.

WATER AND SEWER SYSTEM

The City of Port Arthur initiated construction of its water distribution system in 1910. The demand for water continued to increase with the growth of the city necessitating expansion of the water supply system. The water treatment plant was constructed in 1926 with a major expansion of these facilities in 1950. The most recent improvements to the plant occurred in 1972 with the conversion from a dry chemical to a liquid chemical feed operation. The plant has continuously provided the users with potable water that is well below the limiting criteria of the Texas State Department of Health (43).

Construction of the sanitary sewage collection system was initiated in 1910 with the construction of 9,350 feet of 6, 8, and 10 inch diameter sewers. The sewerage system has grown continually until now the system contains 729,000 feet of sewers, with 42 inch diameter pipe being the largest. Of the total length of sewers in the city, 596,000 feet is 12 inch diameter or less with 133,000 feet of 15 inch diameter or larger. The system contains 594,000 feet of pipe made of acid resistant materials, the major portion of which is 6 and 8 inches in diameter. Over 60 percent of the pipe over

15 inches in diameter is made of concrete. A skeleton diagram of the principal components of the sanitary sewerage system is shown in Figure 2 with the subsystems utilized in the study identified.

The Texas State Department of Health in their "Design Criteria for Sewerage Systems" specify a design velocity of 2 feet per second for sanitary sewers flowing one-half full (44). Under given conditions and where justified, a minimum velocity of 1.6 feet per second flowing one-half full is acceptable. The minimum velocity is applicable to the Gulf Coastal Plain where the 2 feet per second requirement would result in high construction costs. The very flat topography of the Port Arthur area has resulted in a total of 28 lift stations using the lower velocity criteria. If the 2 feet per second requirement would have been maintained throughout the city, a considerably larger number of lift stations would have been required.

The cost of construction of the sewerage system, exclusive of the lift stations and treatment plants through 1967, was $4,214,000. The estimated present worth of the system is $5,704,000. The present worth of the sewage system (structure, equipment, wet well, etc.) lift stations, which originally cost $820,000 is estimated at $1,115,000.

The city did not construct sewage treatment facilities to serve the central area until 1961. Prior to this time the sewage was discharged directly into the Sabine-Neches Canal without treatment. The first of several small sewage treatment plants to serve the outlying or peripherial areas was completed in 1957. In addition to serving the city proper, the main sewage treatment plant treats sewage from the communities of Pear Ridge, Griffin Park, Lakeview and a small area of Groves.

The original cost of sewage treatment facilities, including improvements and additions was $2,103,000. The estimated present worth of these facilities is $2,805,000.

WATER AND SEWAGE CHARACTERISTICS

The City of Port Arthur obtains its water supply from the Neches River via a canal system owned and operated by the Lower Neches Valley Authority. The canal system is an unlined canal that extends from the northern part of the county. The canal serves several cities and industries in addition to the City of Port Arthur. The city maintains two large raw water storage reservoirs that receive water from the canal. The water from the reservoirs is carried by pipeline to the water treatment plant.

The water treatment plant uses chemical coagulation, pH adjustment, sand filters and chlorination. Prior to 1972, the city used dry alum for their coagulation aids and lime for pH adjustment. During 1972, facilities were installed that will use liquid alum and caustic. This should provide a greater control in the chemical treatment.

There are two water quality parameters that are related to the study that

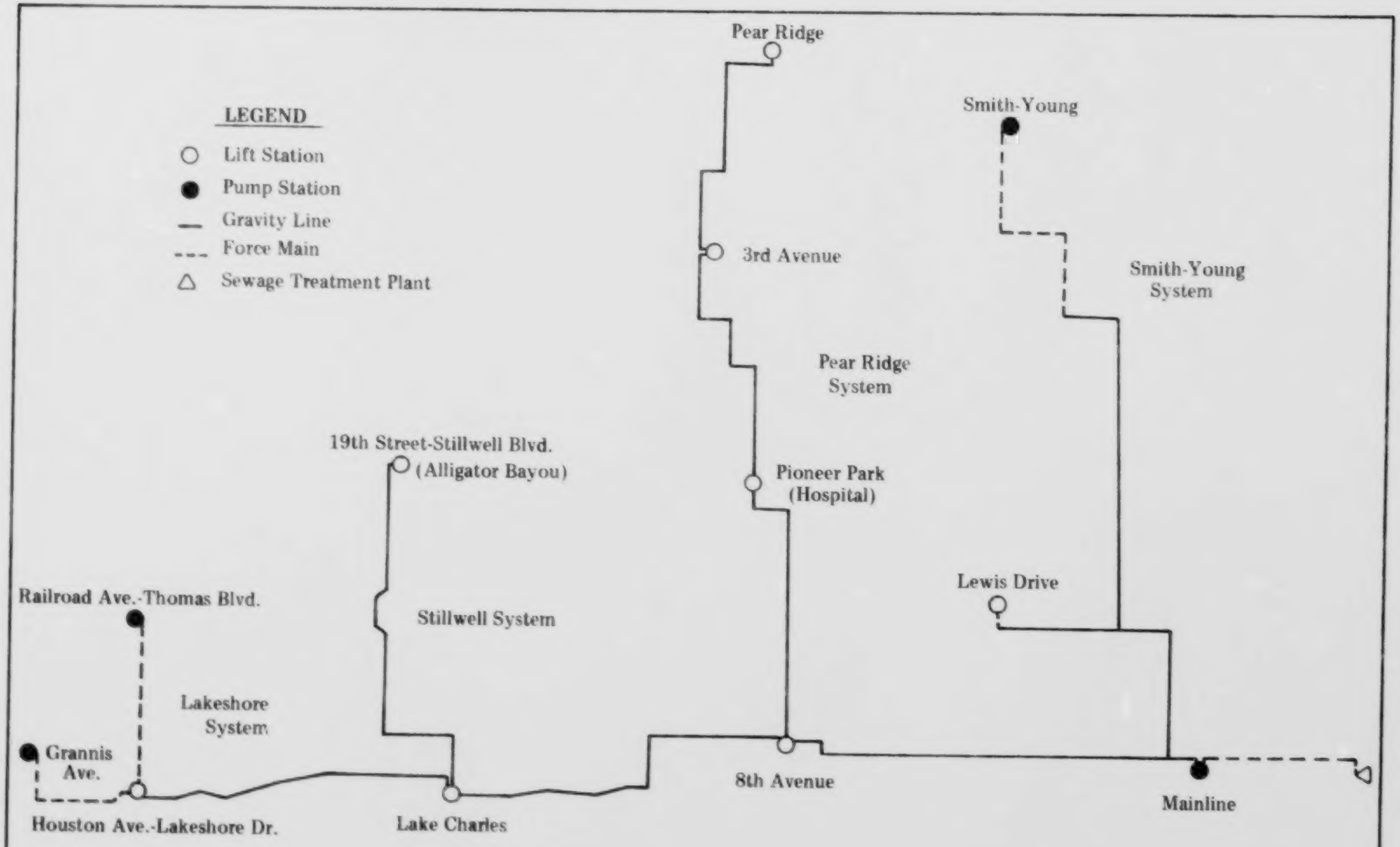

Pear Ridge
Smith-Young
LEGEND
○ Lift Station
● Pump Station
— Gravity Line
- - - Force Main
△ Sewage Treatment Plant
3rd Avenue
Smith-Young System
Pear Ridge System
19th Street-Stillwell Blvd. (Alligator Bayou)
Pioneer Park (Hospital)
Lewis Drive
Railroad Ave.-Thomas Blvd.
Stillwell System
Lakeshore System
Grannis Ave.
8th Avenue
Mainline
Houston Ave.-Lakeshore Dr.
Lake Charles

Figure 2. Principal Components of the Sanitary Sewerage System, City of Port Arthur, Texas

are important to consider. These are sulfates and hydrogen ion concentrations. For a period of 13 years, data indicated an average sulfate content of 21.8 mg/l and a pH of 7.22 for the raw water supply. During this same period the treated water had a sulfate content of 36.1 mg/l and a pH of 7.5. The chemical treatment of water increased the sulfate content of the water by 14.3 mg/l (45). The sulfate level of the treated water is well below acceptable levels (43).

The wastewater treated by the sewage treatment plant is a combination of domestic and commercial wastewater. Although the area is highly industrialized, industrial wastes were not handled by the city prior to 1972. The average biochemical oxygen demand of the influent to the plant for a five year period was 152 mg/l, while the highest single month average for the same period was 308 mg/l.

SEWERAGE SYSTEM FAILURES

Although failures had occurred in the system before 1951, it was not until that year that significant data were recorded on failures within the system. These failures have occurred throughout the entire collection system and have not been isolated to a specific area of the city. Most of the recorded failures have occurred in pipe of fifteen inch diameter or larger.

The records of the city were reviewed for the purpose of evaluating the deterioration rates experienced in the city. The rates were established by dividing the total wall thickness of the pipe by the time period in years between installation and complete structural failure. The rates obtained in this manner will be lower than the actual rate of deterioration. Deterioration rates observed are shown in Table 1.

In many instances the wall thickness reached a critical thickness if not total deterioration prior to complete structural failure. During the inspection survey several pipes were observed in which the crown of the pipe had disappeared without a cave-in. The fact that the line did not cave-in can be partly explained by the arch action of the soil overlying the pipe. Further, the over burden on the pipe when considering this action was not of sufficient magnitude to cause failure. Several unique modes of sulfuric acid attack, which were observed both prior to and during the study, will be discussed later.

Discription of Deterioration

At the initiation of the study, a survey was made of the collection system to access the condition of the sewers and obtain information concerning the character of failures. Throughout the entire study these characteristics were noted to complete the failure descriptions. The surveys of the sewerage system provided valuable information concerning the mode of failure of concrete sewer pipe attributable to hydrogen sulfide.

The very old sewers that demonstrated severe deterioration were character-

Table 1

DETERIORATION RATES OF CONCRETE SEWER PIPE

PORT ARTHUR, TEXAS

LOCATION	Pipe Diameter (inches)	Year in Service	Year of (1) Failure	Years of Service	Wall Thickness (3) (inches)	Deterioration Rate (inches/year)
19 & Stillwell Lift Station to Lake Charles Lift Station	24	1951	1967	16	2 1/8	0.133
3rd Avenue Lift Station – south	18	1951	1966	15	1 1/2	0.100
Smith-Young Force Main Discharge to 25th Street	15	1957	1967	10	1 1/4	0.125
West of Lake Charles Lift Station	30	1961	1966	5	2 3/4	0.55
Along West Thomas Blvd.	15	1957	1967	10	1 1/4	0.125
Pioneer Park (Hospital Lift Station) to 5th	30	1951	1967	16	2 3/4	0.172
Stillwell Blvd.	24	1951	1965	14	2 1/8	0.133
Pioneer Park	30	1951	1970	19	2 3/4	0.144
El Vista	8-15	1956	1967	11	3/4 to 1 1/4	0.114
El Vista	18	1957	1969	12	1 1/2	0.125
Port Acres	15	1956	1971 (2)	15	1 1/4	0.083

(1) Some failures actually occurred earlier but were not reported until the date shown

(2) Most recent failure

(3) Standard Strength – non-reinforced

istic of most published or observed conditions. The crown of the pipe showed the greatest magnitude of loss of wall thickness. From the crown of the pipe the thickness tappered to no loss of material at the minimum flow line. In most cases, at the point of contact with the low flow line, a second point of severe deterioration was observed; however, the loss of material was less than at the crown and represented only a small band parallel with the water line. Below the flow line or pipe invert, no deterioration of the concrete was observed. In all instances, the deterioration appeared to be uniform throughout the entire length of the sewer. Most of these sewers had a series of ripples at the crown. This rippling effect was created by the reinforcing steel imbedded in the concrete pipe. The concrete on either side, i.e. up-or-downstream, was recessed from the location of the steel. There were several instances in which all traces of the steel at the crown had been removed.

Concrete sewers installed in the 1960's provided a different view of the mode of failure. One major trunk line was entered at every manhole and observed. The deterioration observed was quite different from that observed in older sewers. First, there was only a very minor trace, if any, of deterioration observed upstream from the manhole. Downstream from each manhole various conditions were observed that are worthy of note.

Where the manhole was installed in a straight segment of the sewer, severe deterioration was observed immediately downstream. This was characterized by exposed aggregate where the mortar had been destroyed by the sulfuric acid attack and washed away during peak periods leaving the aggregate exposed. Closer investigation revealed the most severe damage appeared to occur on only the first two or three joints downstream. In some of the manholes, the attack at the manhole was of such a degree that the steel was exposed; however in the second or third joint downstream the steel was not exposed. The conditions noted prompted an investigation of the same sewer at a point between manholes. An excavation was made exposing the pipe and a segment of the crown was removed for observation. The crown of the pipe at this point had lost less than one-half inch and a good cover was still provided for the steel.

As previously cited, one of the unusual facets of hydrogen sulfide attack of concrete pipes is that two distinct systems are required, one void of free oxygen and one requiring free oxygen. The oxygen required for the aerobic cycle and final conversion of the hydrogen sulfide to sulfuric acid comes from manholes in the sewer. Apparently, the movement of the air entering the sewer at manholes tends to move downstream. This condition coupled with the turbulence at the manhole which releases the hydrogen sulfide gas provides the proper percentages for the reaction to be continuous. The hydrogen sulfide released is also apparently swept downstream. The explanation for the movement of air downstream is that the sewage tends to move the air by friction at the interface. This is not to imply a strong movement of air but a movement of sufficient magnitude to force a downstream movement of both air and gas. The implications of the character of failure described and apparent cause are quite significant and should perhaps be given consideration in future designs.

The same trunkline as previously described changes direction at several points. The line between manholes remains straight. At each point where a change in direction existed, the manhole was entered and observations noted. As in the straight sections, the line upstream was essentially free from deterioration. Downstream of the manhole a most unusual attack of the pipe was observed.

The crown of the pipe downstream of these manholes although demonstrating deterioration, was not the point of most severe attack. The most serious attack was near the water line and occurred primarily in the area of the spring line and the upper quadrant tapering to the crown and opposite quadrant. This deterioration occurred only on the outside radius of the change in direction. At these changes in direction, the momentum of the sewage was carried up the sides of the pipe on the outer radius while being depressed on the inner radius. No deterioration was observed on the inner radius of the pipe at the change in direction. Hydraulic action on the face of the pipe at the outer radius is greater than normally experienced in a straight pipe thereby maintaining a continuous washing of the surface.

The only explanation for the character of failure observed is that the high degree of moisture found in this area tends to absorb more hydrogen sulfide and oxygen than other quadrants of the pipe. The opposite side as well as the crown of the pipe at these points was relatively dry compared to the side where severe damage had occurred. The major damage was observed on the first joint of pipe downstream with the second joint of the pipe demonstrating a similar but lesser degree of deterioration. Further downstream the attack on the concrete appeared to occur in the crown of the pipe.

Throughout the entire sewerage system one zone of distinct hydrogen sulfide attack was always noted. This was the gravity line immediately downstream of the force main or lift station discharge, with the degree of severity always being greater near the discharge point and decreasing downstream. This contributes to the general philosophy that the force mains are the principle hydrogen sulfide generators in a sewage collection system. In all lines observed, the magnitude of attack and the distance downstream where deterioration was observed appeared to be a function of the sulfide levels measured at the discharge points.

The preliminary work performed in selecting sampling points and treatment locations revealed an additional area of concrete deterioration. This was the mortar in manholes and the wet wells at lift stations. In most instances, the degree of attack at wet wells was much more severe than at manholes.

The damage at lift stations appeared to be uniform at the cover with less severe attack on the walls. This is not to infer that damage to the walls was not reaching critical proportions. A report submitted to the City Council concerning the condition of wet wells in the sewerage system noted that the cover of several wet wells and the walls of one particular station had experienced an alarming degree of deterioration and that failure was imminent (47). While plans were made to either rebuild or abandon these wet wells, guard rails were installed to prevent excessive loads from being imposed on the structure.

Although not directly related to the descriptions of deterioration, a result of the deterioration was noted and deserves mention. During the initial survey and throughout the course of the study, a condition was observed in gravity lines which created many problems and contributed to undesirable flow conditions in the sewers. The continued deterioration of the mortar binder of the concrete pipe resulted in the freeing of aggregate which dropped to the invert of the pipe. The low velocities permitted by the Texas State Department of Health were insufficient to flush the debris to the wet wells where it could be removed. The aggregate formed traps which hold the sand and grit from the mortar resulting in an ever increasing buildup of materials on the bottom. This buildup results in two undesirable conditions. First, the invert is changed from a smooth, circular shape to an irregular flat bottom. This has the effect of altering the flow characteristics by changing both the hydraulic radius and the roughness. The net effect of the debris is to further reduce flow velocities which were inadequate to begin with. In addition to the undesirable effect on flow characteristics, the irregular rough surface traps large amounts of organic matter. The material removed from the invert was very granular and black in color. After washing and allowing to lay on the ground for several days, the material took on the appearance of sand and gravel.

One cubic centimeter of this material was carried to the laboratory for analysis. Upon dewatering, it was placed in a liter of distilled water. After mixing, the solution was tested for sulfides and C.O.D. The sulfide content, which was primarily dissolved, reached 16 parts per million. The C.O.D. of the material approached levels characteristic of industrial waste water.

The sampling of the gravity lines and manholes was very difficult due to this buildup of material, particularily during low flows. During these periods of low flow it was almost impossible to obtain a sample that did not contain some of the debris.

SULFIDE LEVELS IN SANITARY SEWERAGE SYSTEM

The continuing collapse of sanitary sewers led to an investigation to ascertain the level of sulfides that exist in the sanitary sewerage system. Although the study was not comprehensive, it did report sulfide levels (2). The study only reported total sulfides and did not give values for dissolved sulfides and pH which are necessary to determine hydrogen sulfide content of the sewage (25). Sulfide levels in mg/l that have been observed are shown in Figure 3 and identified by the referenced source listed in Section XIII.

Pomeroy reported a dissolved sulfide concentration of 0.1 m g/l would be expected to cause corrosion at a rate of one inch per decade (21). Hydrogen sulfide concentrations of 0.2 mg/l have been reported as the level at which corrosion begins (55). The total sulfide levels for the sanitary sewerage system as shown in Figure 3 would explain the high rate of corrosion preiously reported for Port Arthur. Additional information concerning sulfide levels will be presented in SECTION VI, DISCUSSION OF INDIVIDUAL SYSTEMS.

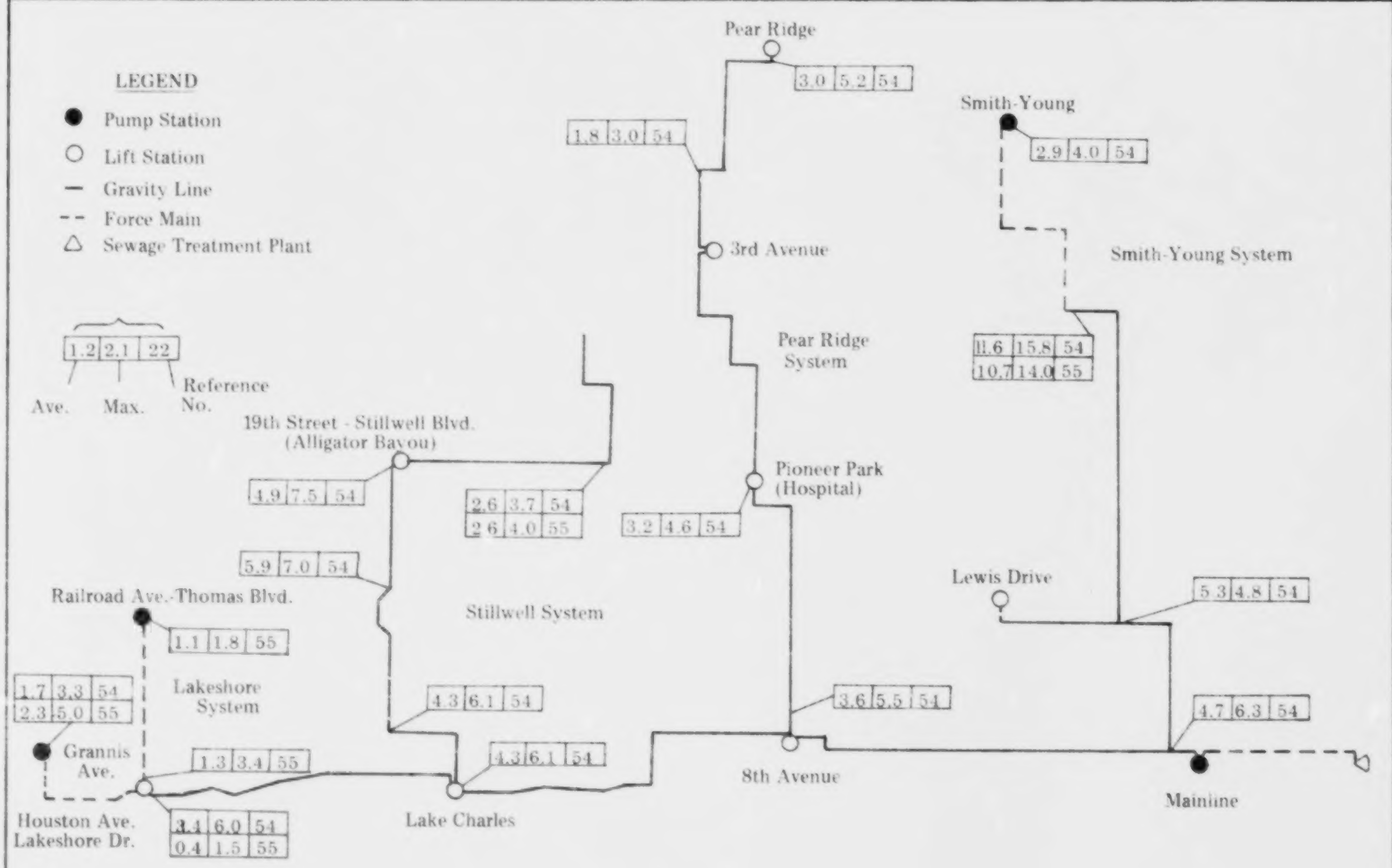

LEGEND
● Pump Station
○ Lift Station
— Gravity Line
- - Force Main
△ Sewage Treatment Plant
1.2 2.1 22
Ave.
Max.
Reference No.
Pear Ridge
3.0 5.2 54
1.8 3.0 54
3rd Avenue
Pear Ridge System
Pioneer Park (Hospital)
3.2 4.6 54
Smith-Young
2.9 4.0 54
Smith-Young System
11.6 15.8 54
10.7 14.0 55
Lewis Drive
5.3 4.8 54
4.7 6.3 54
Mainline
8th Avenue
3.6 5.5 54
19th Street - Stillwell Blvd. (Alligator Bayou)
4.9 7.5 54
2.6 3.7 54
2.6 4.0 55
5.9 7.0 54
Stillwell System
4.3 6.1 54
4.3 6.1 54
Lake Charles
Railroad Ave.-Thomas Blvd.
1.1 1.8 55
Lakeshore System
1.7 3.3 54
2.3 5.0 55
Grannis Ave.
1.3 3.4 55
Houston Ave. Lakeshore Dr.
3.4 6.0 54
0.4 1.5 55

Figure 3. Total Sulfide Levels in the Port Arthur Sanitary Sewerage System

SECTION V

DESCRIPTION OF CONTROL METHODS

The City of Port Arthur's Water and Sewer Study Committee considered various methods to control the odor and concrete corrosion problems caused by hydrogen sulfide. After reviewing the various methods of control, the Committee recommended the use of oxygen as a possible control method. Two sources of oxygen were to be used: air, provided by blowers, and pure oxygen, initially delivered at the site in trailers and later provided by higher capacity cryogenic tanks. Special considerations were given to each source of oxygen and injection method evaluated, and a general discussion of these will be given.

OXYGEN GAS INJECTION - FORCE MAIN

Oxygen gas was first selected for use in force mains and was later used in conjunction with U-Tubes. There were several reasons for the selection of pure oxygen. First, the total volume of gas injection would be considerably less than with air which contains only 21 percent oxygen. Not only would the total volume be less but all of the gas would be available for chemical oxidation or biological action.

There have been several studies involving the injection of air, but they considered chemical-biological actions without regard to head losses. The age of the pumps in the Port Arthur Sewerage System and the marginal available head was of concern in the selection of the oxygen source. It was felt that the lower gas volume that resulted from using pure oxygen would create less system losses and minimize the potential of air locking.

Previous studies using blowers for air injection reported conditions of excessive noise associated with the compressors. The sites selected for control in the Port Arthur Sewerage System were all located in residential areas where the sound of the blowers would be undesirable. Also, the dry pits of the lift stations were space limited and could not accomodate the air compressors. The use of gaseous oxygen represents a noiseless operation with no serious problems associated with aesthetics.

The decision to use gaseous oxygen brought about one serious concern. This was the potential for explosions as expressed by several concerned citizens. The potential for explosion is real when oxygen is mixed with combustible gases and the presence of hydrogen sulfide accentuated this. This question was presented to a chemist who acknowledged the fear, however not without qualifications (47). Sewer gases when mixed with air (oxygen) in a dry or nearly dry condition, will explode when sparked by some source of fire or catalyst. The presence of water or water vapor serves as a stabilizing factor thereby reducing the potential for an explosion. The injection of oxygen into the liquid stream would not create a hazardous condition. The gases present would be oxidized and further generation of combustible gases would not be possible under aerobic conditions.

There is always a fear of gasoline and other combustible materials being discharged into the sewerage system. Most of these are of a lower specifi gravity than water and would therefore be trapped in the wet wells. Only in a vary unusual circumstance would these materials be drawn into the force main.

The concern in the use of oxygen was not completely dispelled and special precautions were taken. The construction specifications required that all piping, valves, and other equipment be throughly cleaned and be free from oil or grease prior to installation. Further, all joints were to be sealed by use of a special teflon tape.

The oxygen from the tank passed through a control valve for flow regulatio a rotameter for flow measurement, and a solenoid valve prior to entering the diffusion equipment. The solenoid control valve was set to open ten seconds after the pump cycle starts and to close when the pump stops. Thi measure was taken to assure that the oxygen would always be injected direc into the sewage.

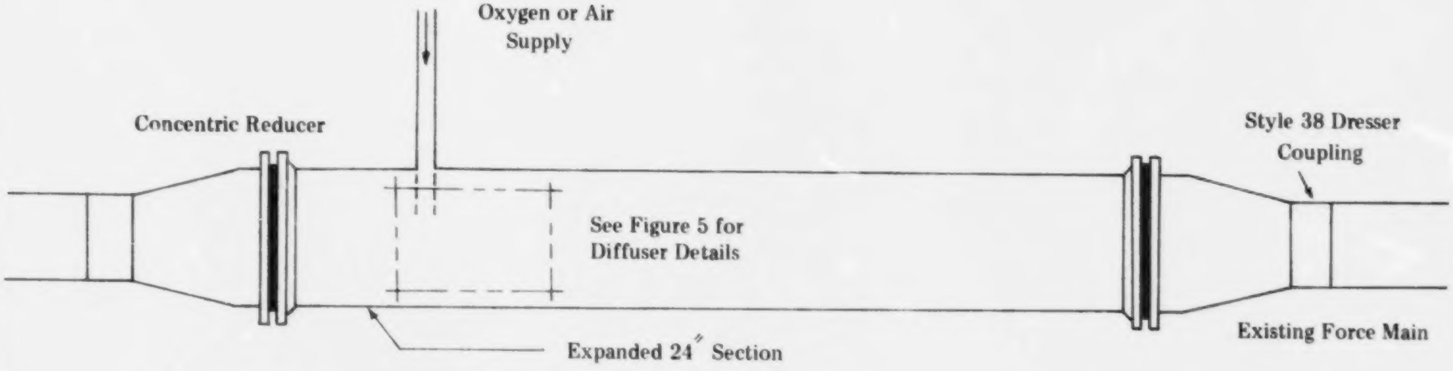
There were three methods of injection utilized at various stages in the study. The initial installations utilized an enlarged section of pipe out side the lift station with three diffusers installed. The piping arrangement is shown in Figure 4, and the diffuser arrangement shown in Figure 5. The use of the diffusers raised a serious question concerning operation an maintenance. It was felt that the piping and diffusers would serve to tra rags and other debris which would block the flow. After one year of opera tion, one of the sections was opened and found to contain only a minor amo of debris that would not interfere with flow conditions. The original des did not provide a manway for access to the diffusers which should be insta Blockage of the flow in the original configuration would represent a major task for removal for maintenance purposes.

Two other methods of injection were later tried in the study. The first o these consisted of drilling and tapping with the oxygen injected without diffusers. The next was insertion of a curved copper tube with the bend in the downstream direction. The reason for this was to prevent the colle tion of rags. Each copper tube had a series of small diameter holes along the length in two rows with the end of the tube closed. The purpose was to reduce the bubble size.

AIR INJECTION - FORCE MAIN

The application of air injection has been used with success in various locations in the control of hydrogen sulfide. Air injection was planned at one location after a period of operational experience with oxygen. This would permit an economic evaluation of the oxygen sources for hydrogen sulfide control as well as provide operation and maintenance experience.

The methods of injection at the first installation was identical to that


Oxygen or Air
Supply
Concentric Reducer
Style 38 Dresser
Coupling
See Figure 5 for
Diffuser Details
Existing Force Main
Expanded 24" Section

Note: Not to scale

Figure 4. Force Main Piping Arrangement

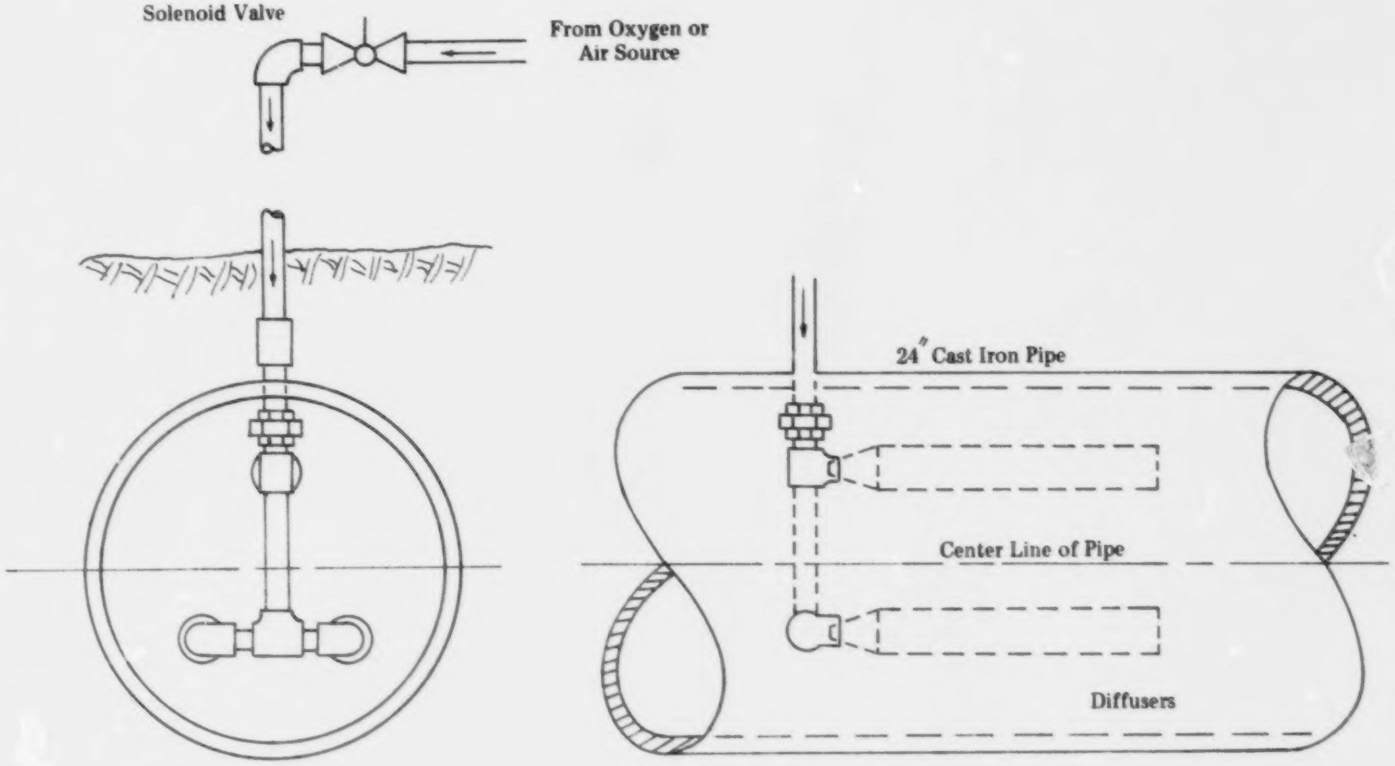

Solenoid Valve
From Oxygen or Air Source
24" Cast Iron Pipe
Center Line of Pipe
Diffusers

Figure 5. Typical Diffuser Arrangement for 24" Cast Iron Pipe

first used with oxygen. This was the expanded section with diffusers as shown in Figures 4 and 5. The expanded section had the effect of reducing the velocity and increasing the pressure. The increased pressure would increase the solubility while the diffuser would provide greater surface area for the air bubbles thereby increasing the potential for oxygen transfer.

The system was designed in a manner that would permit either continuous air feed or air feed only during pump operation. The blowers selected for the original installation were oil-free to prevent the introduction of oil and grease into the sewage.

A second method for injecting air into a force main was selected and evaluated during the study. This method involved a straight pipe flush with the crown of the force main. Air injection was also used in conjunction with a U-Tube aeration device. This represents a special condition and discussion will be found in the section dealing with this method.

OPEN TANK AIR INJECTION

A sewage lift station as opposed to a sewage pump station require a different approach to the hydrogen sulfide problem. The two types are differentiated as follows: (a) The lift station serves to lift the sewage from a lower elevation to a higher elevation for gravity flow or employs a very short force main and (b) the sewage pump station is associated with force mains of considerable length. The sewage lift stations that had a history of hydrogen sulfide problems did not serve as generators but served to release previously generated hydrogen sulfide gas in the vicinity of the turbulence created at the discharge point.

Consideration was given to the application of a large circular aeration tank with diffusers at the periphery of the tank. The tank would serve to provide detention time for the oxidation of the sulfides and permit conversion of the sewage to an aerobic condition. The major problem as previously stated was the arrival of perviously generated sulfides and not additional generation.

Upon careful consideration of the problem, this method of air injection was abandoned in favor of the pressure tank. The basic reason for elimination of this method was that there was no assurance that the sulfides would be oxidized and that the tank would merely serve to strip out the gas. In this instance, severe odor problems could be anticipated at the installation.

PRESSURE TANKS

The application of a pressure tank of air injection is based upon Henry's Law. Henry's Law may be stated as follows: "The weight of a gas that dissolves in a definite volume of liquid is directly proportional to the pressure at which the gas is supplied to the liquid" (4). This means that if one gram of gas dissolves in a liter of water at one atmosphere, then two grams will dissolve at two atmospheres.

There are three factors that control the solubility of a gas in a liquid and these are: (a) the nature of the gas and the solvent, (b) the pressure at which the gas is applied (Henry's Law) and (c) the temperature. It is therefore obvious the role pressure plays for a system of air injection into sewage. One additional comment concerning pressure is important. The effect of pressure does not follow Henry's Law when a reaction takes place with the solvent. In the application of oxygen, there is no reaction with the solvent (water); however, reaction will occur with the sulfides.

The basic concept applied for pressure tank air injection was for a continuous flux of sewage with a controllable detention time. The air would be continuously injected at an elevated pressure through diffusers, with a blowoff at the top of the tank with excess air piped to the discharge line. The sewage would flow from the bottom of the tank to the top and discharge through an overflow. The flow schematic is shown in Figure 6.

This installation was selected to meet the needs of certain lift station configurations in the Port Arthur Sewerage System. There were several lift stations with records of hydrogen sulfide problems. The sulfides were found to exist in the wet wells and the turbulence at the discharge released the gas. These stations operate strictly as a lift station (no force main) or they operate with a very short force main with only minor generation of additional sulfides. In these instances, it was felt that air/oxygen injection would not be successful primarily as a function of detention of contact time. A more serious shortcoming was found in the stations with short force mains where oxygen injection was applied. This was a complete separation of the oxygen and sewage resulting in two phase flow. This will be more fully discussed under Data Collection and Analysis.

The pressure tank for air injection therefore had two basic purposes. It increased the solubility of oxygen in the sewage by operating above atmospheric pressure. The second factor was that the high degree of mixing, by using variable spaced diffusers, and the detention time, would assure that the sulfides would be oxidized prior to discharge. (The mixing also served to prevent short circuiting through the pressure vessel).

U-TUBE AERATION DEVICE

The application of the U-Tube aeration device represents a recent development for oxygen transfer. The first reported work was by Bruijn and Tuinzaad in 1958 (48). Additional work on U-Tubes was reported by Speece, Adams and Wooldridge in 1969 (49), and by Speece and Orosco in 1970 (50). Concurrent with this work was a separate study of U-Tube aeration by Rocketdyne for the Environmental Protection Agency (51). The work by Rocketdyne served as the basis for design of the U-Tubes used in this study.

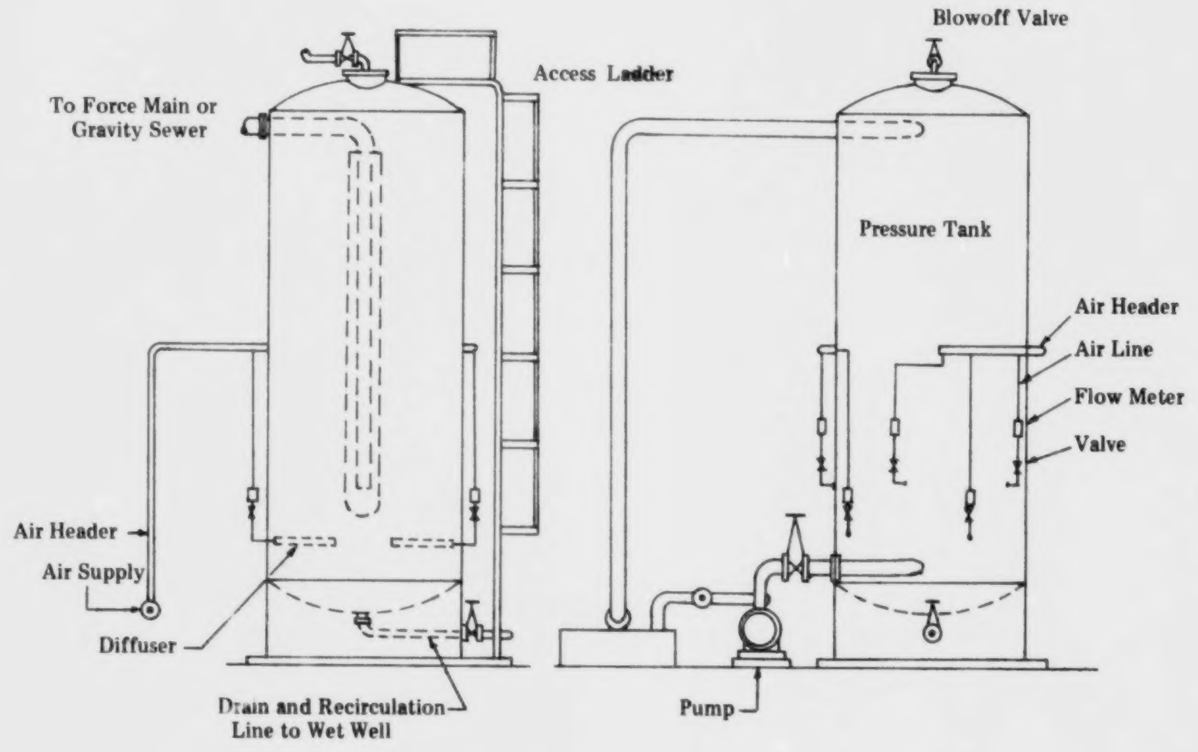

To Force Main or Gravity Sewer
Access Ladder
Blowoff Valve
Pressure Tank
Air Header
Air Line
Flow Meter
Valve
Air Header
Air Supply
Diffuser
Drain and Recirculation Line to Wet Well
Pump

Figure 6. Pressure Tank Air Injection

There are two basic elements of the U-Tube aeration process. Air is entrained in the liquid flow by an aspirator device (venturi) or by compressed air. Following air entrainment, the flow regime is changed to increase the pressure and provide additional residence time. The configuration of the U-Tube and the method of air entrainment can take various forms, however the basic configuration is shown in Figure 7.

The U-Tube application in Port Arthur was at sewage lift stations and located within the dry pit although several other applications have been demonstrated (52). There were two sources of oxygen employed with the U-Tubes in the Port Arthur Sewerage System. One design called for compressed air while the second utilized pure oxygen.

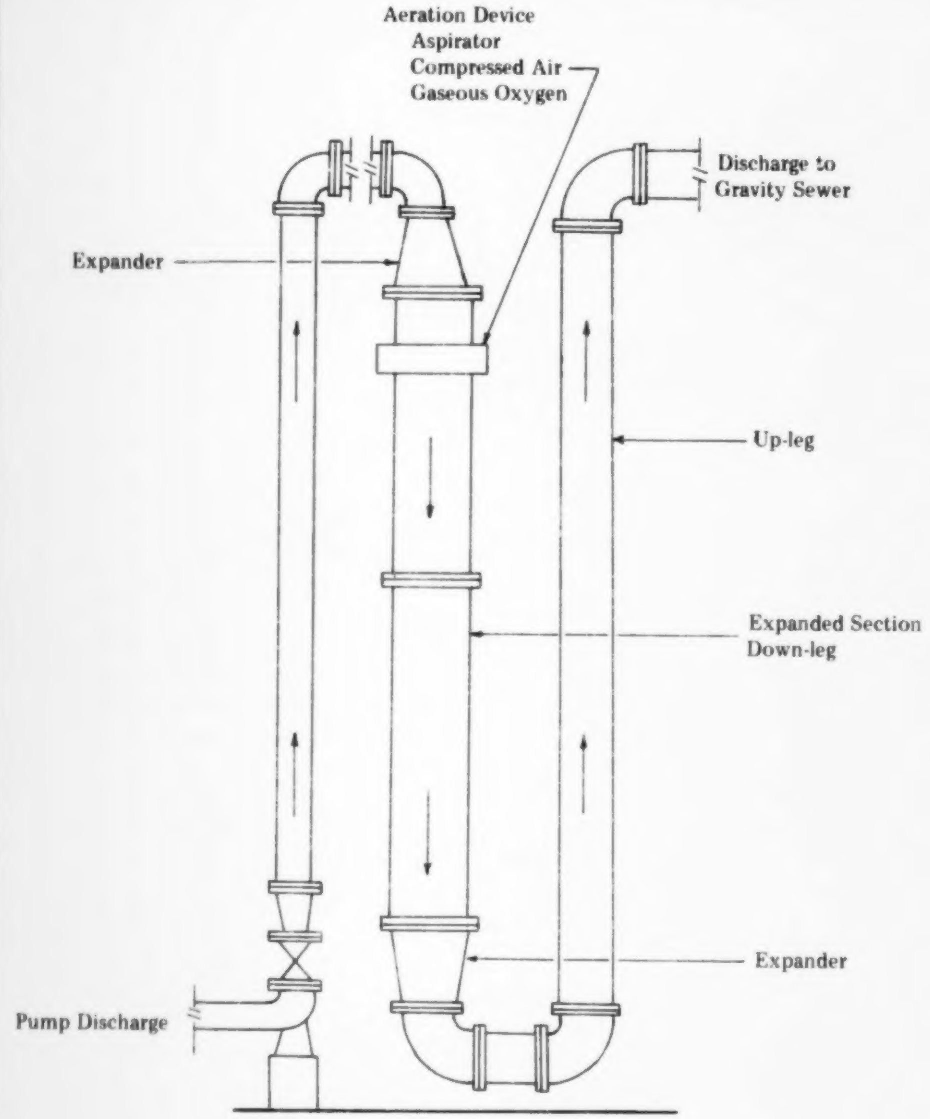

Aeration Device
Aspirator
Compressed Air
Gaseous Oxygen
Discharge to
Gravity Sewer
Expander
Up-leg
Expanded Section
Down-leg
Expander
Pump Discharge

Figure 7. Typical U-Tube Installation

SECTION VI

SULFIDE PROBLEMS AND CONTROL RESULTS

LAKESHORE SYSTEM

The Lakeshore System involves three lift or pump stations, two of which have sulfide control measures installed. The three stations are Grannis Avenue Pump Station, Railroad Avenue-Thomas Boulevard Pump Station and the Houston Avenue-Lakeshore Drive Lift Station. All three stations discharge into a common point, a junction box, which is an integral part of the Houston Avenue-Lakeshore Drive Lift Station. From the junction box, the sewage flows by gravity to the Lake Charles Lift Station, the terminal point of both the Lakeshore and Stillwell Systems. Details of the system are shown in Figure 8.

Protection of the gravity line in this system was a major concern. This line is approximately 10 years old and consists of 21 and 24 inch diameter concrete pipe, a significant capital investment. Although there are not any large sections of this line in imminent danger of failure, short sections downstream of those manholes where the line changes direction are approaching critical condition. Photographs of portions of this line are shown in Figure 9.

In addition to the corrosion of the pipe, odor problems have also persisted along this gravity sewer. This problem has been most severe at the Lake Charles Lift Station. As seen in Figure 10, the wet well at this station has undergone severe deterioration and its structural stability would be classified as critical with a potential for failure at any time. The desirability of bringing the hydrogen sulfide problem in this system under control is obvious.

Sulfide Levels

Sulfide levels were monitored at sampling stations located at wet wells, discharge points (junction box) and selected points in the interceptor. The results of the monitoring program will be discussed in sequence from the upstream stations to the end of the gravity line at the Lake Charles Lift Station wet well.

Grannis Avenue Pump Station

This station is characterized as a low capacity station in which the sewage has a long detention period in the wet well. The station is equipped with two pumps that alternate. During one test period, the pumps operated for an average of ten minutes per hour. During high flow periods, these pumps cycle frequently due to pump capacity and wet well storage. The reverse is true during low flow periods. The station receives sewage with high levels of sulfides and has a history of odor complaints.

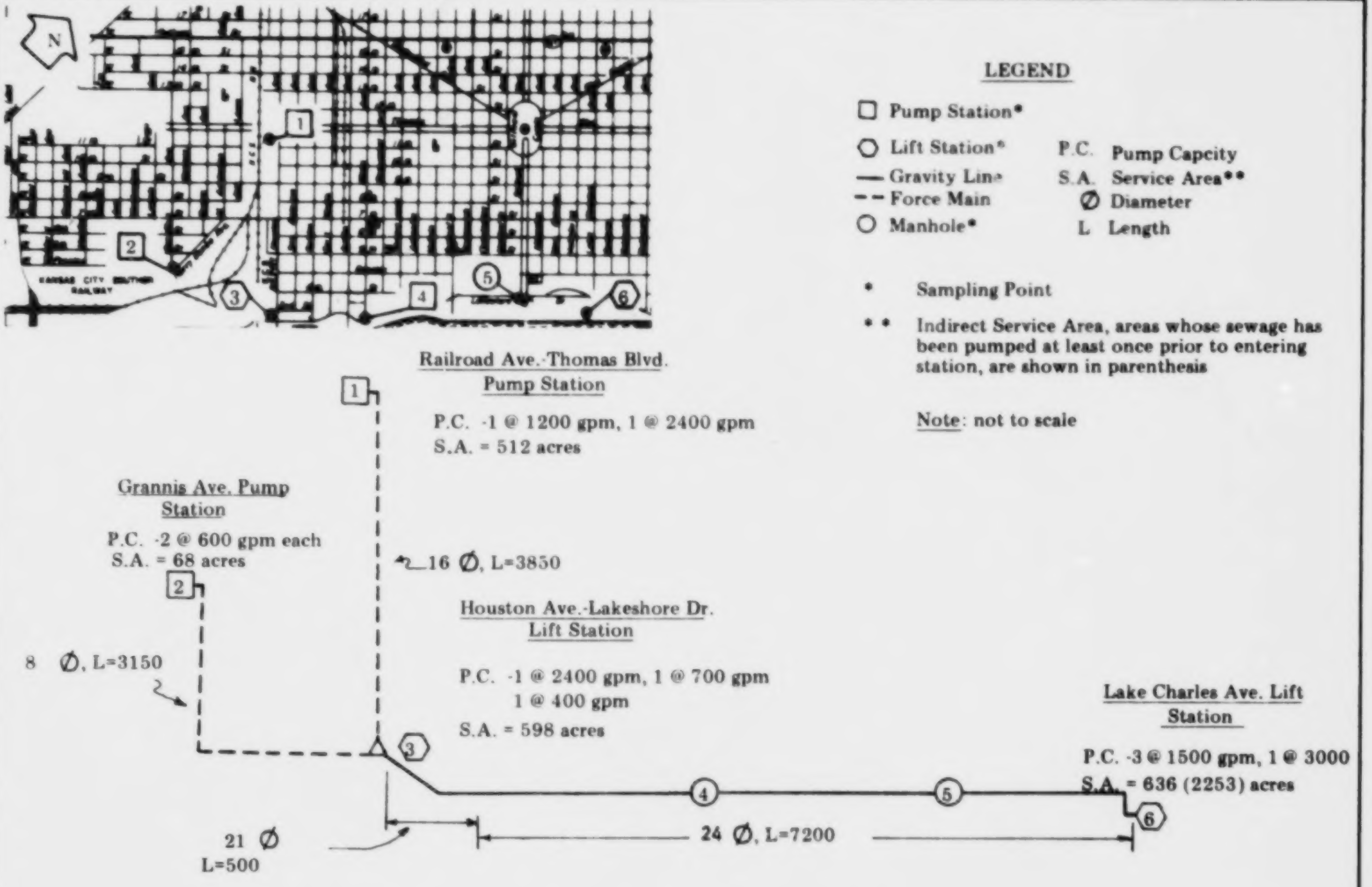
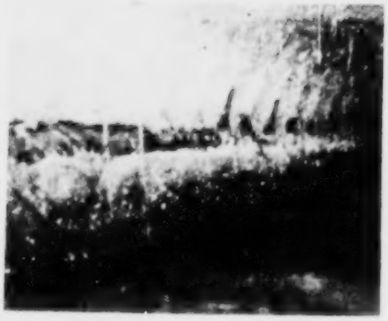

N
KANSAS CITY SOUTHERN RAILWAY
1
2
3
4
5
6
LEGEND
□ Pump Station*
⬡ Lift Station*
— Gravity Line
-- Force Main
○ Manhole*
P.C. Pump Capcity
S.A. Service Area**
Ø Diameter
L Length
* Sampling Point
** Indirect Service Area, areas whose sewage has been pumped at least once prior to entering station, are shown in parenthesis
Note: not to scale
Railroad Ave.-Thomas Blvd. Pump Station
P.C. -1 @ 1200 gpm, 1 @ 2400 gpm
S.A. = 512 acres
Grannis Ave. Pump Station
P.C. -2 @ 600 gpm each
S.A. = 68 acres
16 Ø, L=3850
Houston Ave.-Lakeshore Dr. Lift Station
P.C. -1 @ 2400 gpm, 1 @ 700 gpm
1 @ 400 gpm
S.A. = 598 acres
8 Ø, L=3150
Lake Charles Ave. Lift Station
P.C. -3 @ 1500 gpm, 1 @ 3000
S.A. = 636 (2253) acres
21 Ø
L=500
24 Ø, L=7200

Figure 8. Lakeshore System



View downstream; left side. First joint downstream at manhole. Sewer changes direction at this location.

View downstream: right side. First joint downstream at manhole. Sewer changes direction to left at this location.

Figure 9. Deterioration at Manholes - Lake Charles Interceptor

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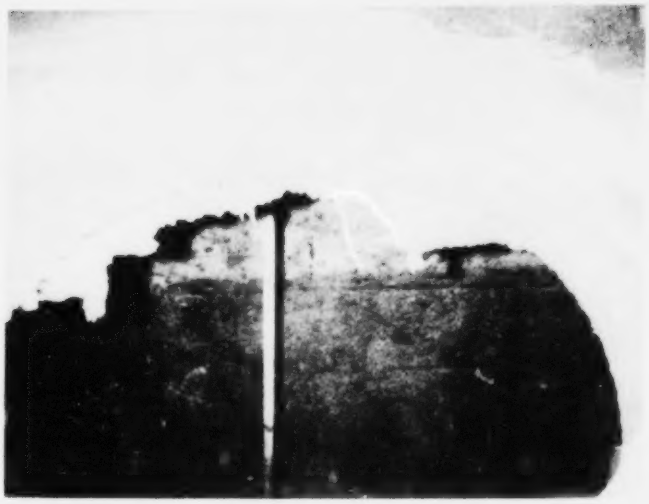
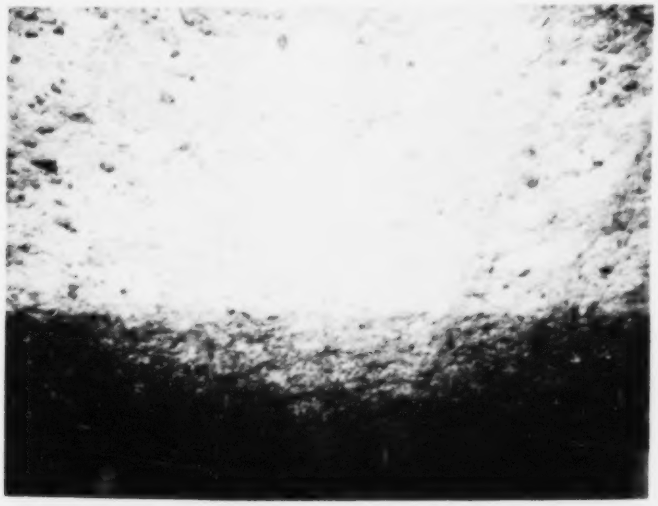


Deterioration at the top of the Lift Station. Note exposed rebars.



Deterioration of wet well wall. Note line traces. These are due to rust along tracing rebars in wall.

Figure 10. Deterioration in the Lake Charles Lift Station Wet Well

Samples were obtained from the wet well and at the point of discharge. Data collected for the station are given in Table 2. The first two sample periods indicated a decrease in sulfides which is contrary to what would be expected. This decrease can partly be explained by the fact that some hydrogen sulfide gas was released, apparent by odors of the gas, by turbulence in the junction box.

The samples obtained on July 21, 1969, during a period of high infiltration, provide a good example of the sulfide generation in this force main. The level of total and dissolved sulfide in the wet well effluent which had a trace of dissolved oxygen increased by 4.3 mg/l and 3.0 mg/l, respectively. The generation potential was much more dramatically indicated by the samples collected on July 30, 1969 where there was an increase of 9.5 mg/l of total sulfides and 7.4 mg/l of dissolved sulfides.

Railroad Avenue & Thomas Boulevard Pump Station

The city has not received as many odor complaints on this station as it has on other stations within the Lakeshore System; however, the exposed aggregate on the inside walls of the wet well evidence sulfuric acid attack.

In 1969, Wright reported some average values for total sulfides at this station (53). As seen in Table 3, Wright reported the average increase in total sulfides to be 2.2 mg/l. Samples taken on July 2, 1969 indicated a higher sulfide level than had been previously reported. The sulfide level increased from 0 to 15 and 14.6 mg/l respectively for total and dissolved sulfides.

The significance of oxygen in controling sulfide generation was indicated by samples collected July 17, 1969. The sample at the wet well contained 4.09 mg/l of dissolved oxygen and 0.3 mg/l of total sulfides. The discharge contained only 0.9 mg/l total sulfides and the dissolved oxygen had decreased to 1.82 mg/l.

Houston Avenue - Lakeshore Boulevard Lift Station

The Houston - Lakeshore Station is important in evaluating the Lakeshore System because it's effluent mixes with the discharge from the previously mentioned force mains. The combined flows then enter the Lakeshore Interceptor. As the station is only a lift station and not recognized as sulfide generator, only discharge data were collected.

Data were collected from June until November, 1969. The summary data are presented in Table 3. The most undesirable characteristic of this sewage, which comes primarily from the downtown area, is the temperature. Average sulfide levels were generally acceptable especially when considering the pH levels. The pH levels would be considered an asset as they were generally in the basic range.

Lakeshore Boulevard Interceptor

The Lakeshore Interceptor was sampled at two intermediate locations and at

Table 2

SEWAGE CHARACTERISTICS
GRANNIS AVENUE PUMP STATION – FORCE MAIN

		PARAMETER					
Date	Sampling Point	Temp. (°C)	pH	Total Sulfides (mg/l)	Dissolved Sulfides (mg/l)	Dissolved Oxygen (mg/l)	BOD (mg/l)
6-29-69	WW*	29	7.0	4.1	3.4	0	137
	D	29	7.0	3.4	3.0	0	198
7-2-69	WW	28	6.9	5.0	3.4	0	150
	D	28	7.0	2.4	1.6	0	174
7-21-69	WW	29	6.8	0.6	0.5	0.5	211
	D	30	7.0	4.9	3.5	0.4	245
7-30-69	WW	29	5.7	2.2	1.6	0	154
	D	29	5.9	11.7	9.0	0	318

* WW - Wet well
D - Force main discharge

Table 3

SEWAGE CHARACTERISTICS

(a) Railroad Ave. - Thomas Blvd. Pump Station - Force Main
[Test Period December 5, 1968 to January 29, 1969]

Sampling Point		Parameter	
		Total Sulfides (mg/l)	Dissolved Oxygen (mg/l)
Wet Well	Ave.	2.8	0
	Max.	6.0	0
	Min.	1.3	0
Discharge	Ave.	5.0	0
	Max.	6.2	0
	Min.	3.0	0

(b) Houston Ave. - Lakeshore Blvd. Lift Station
[Test Period June 27 to Nov. 29, 1969]

	Parameters						
	Temp. (°C)	pH	Total Sulfides (mg/l)	Dissolved Sulfides (mg/l)	DO (mg/l)	BOD (mg/l)	COD (mg/l)
Ave.	32.7	7.8	0.4	0.3	1.2	218	586
Max.	37	10.0	1.5	1.3	4.2	418	1620
Min.	21	6.7	0	0	0	65	76

the terminal point of the interceptor, the wet well at the Lake Charles Lift Station. The sampling points (manholes) are indicated in Figure 8.

Due to the sulfide corrosion in gravity sewers previsously described on page 21, there were significant debris and sludge deposits in the invert of the interceptor. Consequently, it was very difficult to obtain characteristic samples of the flowing sewage without disturbing these solids. During the low flow periods, sampling was not possible.

The data, as shown in Table 4, indicate that the high sulfide levels generated in the force mains are reduced as the sewage moves from the junction box at the Houston-Lakeshore Station to the Lake Charles Lift Station. The reduction is due to the evolution of hydrogen sulfide gas which is evidenced by the corrosion found in the line.

For any condition of flow less than one-half full, the sulfide generation increases as the flow decreases. There were many periods observed in which the flow was less than one-half full. However, because of the release of gas at the points of turbulence further buildup of sulfides in the sewage did not occur.

System Design

The installation of aeration equipment to oxidize the sulfides in the junction box, would have been the most desirable approach for several reasons. First, all three flows could have been treated assuring that the sewage entering the interceptor would be at an acceptable sulfide level; second, control at a single point would have meant equipment installation at one location in lieu of two or three; and lastly, the economics, capital costs, maintenance and operational costs, etc., of one control point would have been more favorable. However, the design of the junction box was such that major renovation would be required to allow such an installation.

Since the Houston-Lakeshore Station was not considered a sulfide generator, the system sulfide control measures would have to be provided at the two pump stations, the principle sulfide contributors. Further, consideration of flows from the two pump stations indicated that the major amount of excess oxygen would have to be added at the Railroad-Thomas Boulevard Station. The flow from this station is approximately ten fold greater than the Grannis Station. Control at the Grannis Avenue Station would be primarily aimed at preventing sulfide buildup in the force main, with the maintenance of a dissolved oxygen residual being secondary. By eliminating the majority of the sulfides from entering the Lakeshore Intercepter and increasing the residual dissolved oxygen of the flows, it was felt that the surface aeration in the sewer would be adequate to oxidize additional sulfides generated in the interceptor. Ideally, the total oxygen supplied would be sufficient to actually retard sulfide generation.

Grannis Avenue Pump Station

The proximity of houses at this station required that noise be kept at a

Table 4

SEWAGE CHARACTERISTICS

Lakeshore Interceptor
[Test Period June 27 - July 31, 1969]

Sampling Point	Parameters *					
	Temp. (°C)	pH	Total Sulfides (mg/l)	Dissolved Sulfides (mg/l)	DO (mg/l)	BOD (mg/l)
Lakeshore Blvd. & Waco Ave.	28.5	7.4	1.9	1.5	trace	111
Lakeshore Blvd. & Stillwell Blvd.	28.5	7.1	1.7	1.4	0	138
Lake Charles Lift Station	29	6.6	1.9	1.1	0	184

* Weighted Average Values

minimum. Secondly, the dry pit configuration would not permit the installation of equipment inside. The force main diameter is 8 inches and length is 3150 feet. Pumping capacity during dry weather is 600 gpm. pure oxygen was the sulfide control measure used at this station. The oxygen equipment was installed adjacent to the pump station. The oxygen equipment and the diffuser arrangement installed for oxygen entrainment are shown in Figures 4 and 5. Details of this installation are shown in Figure 11.

After a period of operational experience, the installation was modified. The force main was tapped downstream from the diffusers and a four inch diameter recirculation line was installed to permit oxygenated sewage to be returned to the wet well. This was done to control odors and corrosion in the wet well.

Operation and Data Analysis

There were no taps provided for sampling directly from the force main and samples of the discharge had to be taken at the junction box which also received the discharge from the two other stations. These two stations could be turned off for only short periods of time as their flow was significantly greater than the Grannis Station. During the pumping cycles of the two stations it was virtually impossible to differentiate flow from the Grannis Avenue Force Main. In addition to these problems associated with sewage flows, there was an objective to maintain as high a level of D.O. as possible at the sacrifice of optimization of the system.

The data collected for various oxygen feed rates are provided in Table 5. One concluding factor of this data is that the force main served as a sulfide generator and this generation can be controlled by injecting pure oxygen. For those oxygen feed rates where data were obtainable, the control of sulfides was accomplished and a residual dissolved oxygen maintained. It appears that the same degree of control would be possible at a lower feed rate.

Railroad Avenue & Thomas Boulevard Pump Station

The location of the station provided more flexibility in the selection of methods for sulfide control. This factor coupled with the length of the force main and its sulfide generation history provide a good opportunity to compare two methods of sulfide control by oxygen on the same system. The injection of pure oxygen was first studied followed by an evaluation of air injection. Details of this installation are provided in Figure 12. The force main diameter is 16 inches and the length is 3850 feet. The pump station capacity during dry weather flow is 1200 gpm.

Either pure oxygen or air could be injected in the sewage through the diffuser system designed for the project (Figures 4 and 5). This station required six diffusers, in lieu of three installed at other locations, to facilitate both oxygen and air injection. This permitted the change of equipment, i.e. from pure oxygen to air, with only minor modifications.

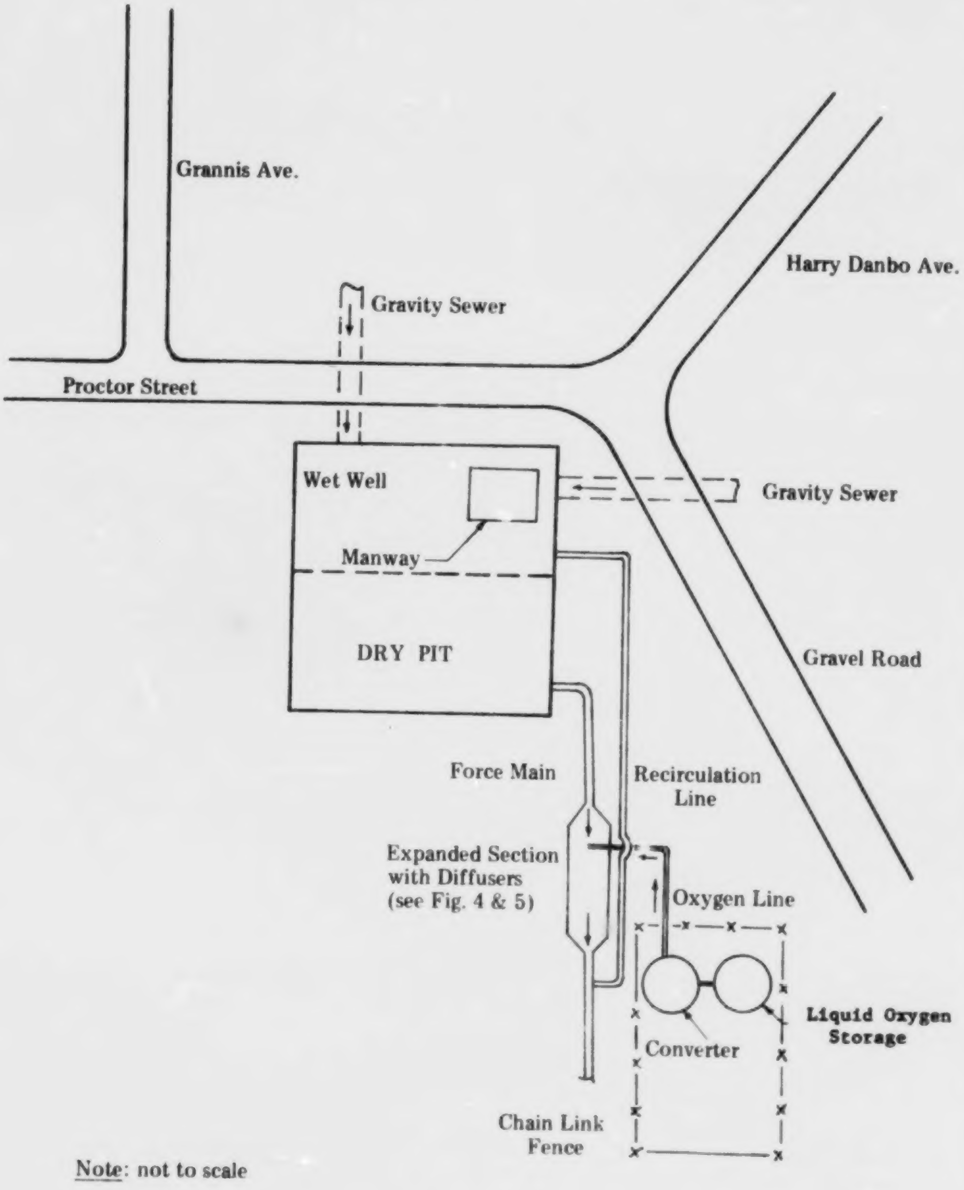

Grannis Ave.
Harry Danbo Ave.
Gravity Sewer
Proctor Street
Wet Well
Gravity Sewer
Manway
DRY PIT
Gravel Road
Force Main
Recirculation Line
Expanded Section with Diffusers (see Fig. 4 & 5)
Oxygen Line
Liquid Oxygen Storage
Converter
Chain Link Fence
Note: not to scale

Figure 11. Grannis Ave. Pump Station

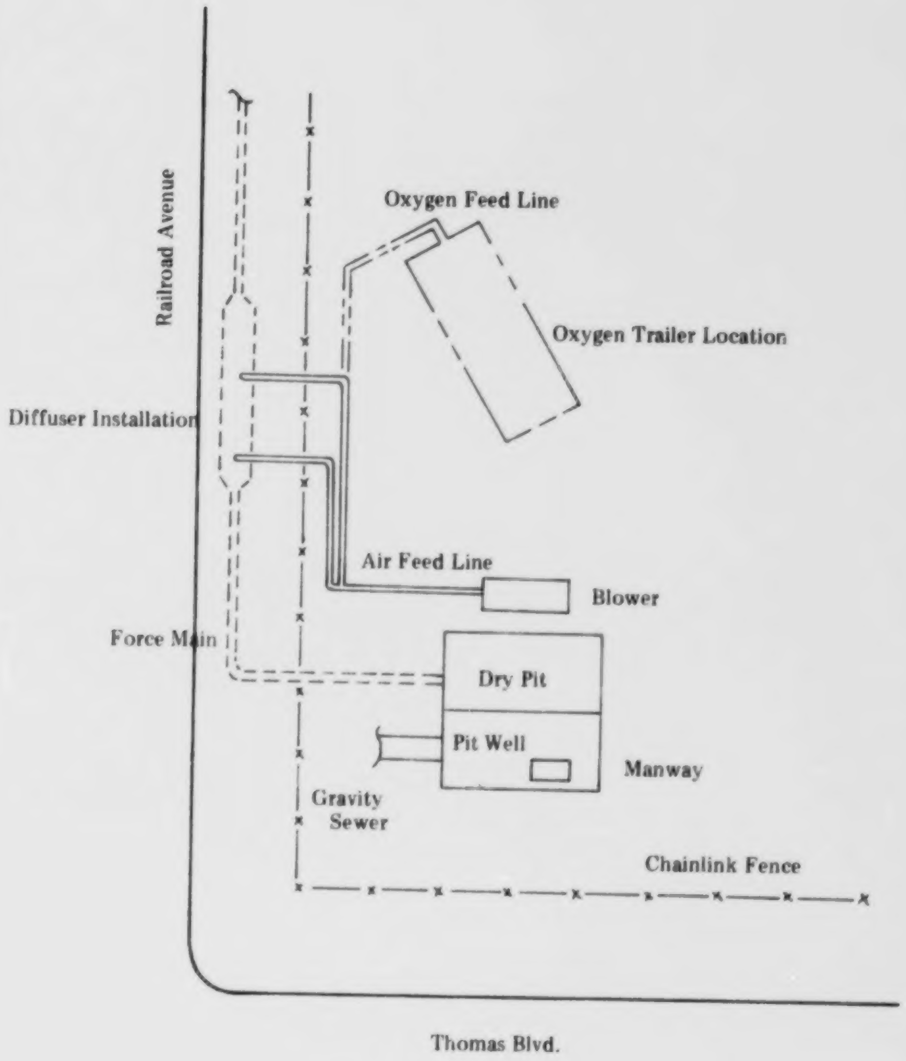
Table 5
OPTIMIZATION OF OXYGEN INJECTION

Grannis Avenue Wet Well - Force Main
[Test Period June 23 - Sept. 9, 1969]

Sampling Point				Force Main Discharge			
Parameter			Wet Well	O_2^* = 0cfm	O_2 = 5cfm	O_2 = 6cfm	O_2 = 7cfm
Sulfides (mg/l)	Total	Ave.**	2.3	6.4	0.9	0.5	0.6
		Max.	5.0	11.7	2.2	2.1	0.7
		Min.	0.6	2.4	0.3	trace	0.5
	Dissolved		1.9	4.6	0.5	0.3	0.3
			3.4	9.0	1.9	1.4	0.3
			0.5	1.6	0.2	0.0	0.2
Dissolved Oxygen (mg/l)			0.05	0.06	4.9	6.5	4.9
			0.47	0.44	8.2	11.7	6.9
			0	0	2.4	2.8	3.0
Biochemical Oxygen Demand (mg/l)			266	256	313	336	457
			402	346	401	342	581
			137	174	240	318	333
Chemical Oxygen Demand (mg/l)			529	538	541	725	687
			826	815	694	970	787
			296	401	386	553	588

* O_2 (Oxygen) Injection Rate into Force Main

** Weighted average



Railroad Avenue
Oxygen Feed Line
Oxygen Trailer Location
Diffuser Installation
Air Feed Line
Blower
Force Main
Dry Pit
Pit Well
Manway
Gravity Sewer
Chainlink Fence
Thomas Blvd.

Figure 12. Railroad Pump Station

The oxygen feed system was equipped with a rotameter that would permit flow variation from zero to 14 cfm. The air compressor was installed without flow measuring equipment which presented some problems in optimization. Variation in air feed was achieved by varying the amount of waste air. This provided a means of varying air flow. However, calculation of accurate air:water ratios was not possible. A rotameter was installed at a later date and more accurate air feed rate data were obtained.

The installation was modified during the study in an effort to control the sulfides in the wet well. A recirculation line downstream of the diffuser returns flow to the last manhole on the gravity line prior to entering the wet well. The return flow, high in dissolved oxygen content, is mixed with the incoming sewage, which contains sulfides except during periods of high infiltration.

Oxygen Injection

Oxygen was injected in the force main from June until September, 1969. During this period, the oxygen feed rate was varied to determine the optimum rate for sulfide control and residual dissolved oxygen. After an oxygen feed rate was set, the station was permitted to operate a minimum of 24 hours to allow the system to adjust. Longer periods between changes in oxygen feed rate and sampling appeared to have little, if any, effect on test results.

The oxygen feed rates at the station were varied from zero to six cfm. Data at one cfm were not obtainable as the rotameter would not stabilize at that rate. The feed rates used would represent an oxygen to water volume ratio of 1.24 to 3.72 percent on an oxygen application of 14 to 43 mg/l. The design of the system did not permit the evaluation of head losses. However based upon pump cycling times, the injection of oxygen did not appear to have any adverse effect on the hydraulics of the system.

The data collected during the optimization study are presented in Table 6. For each parameter listed, the average value of all samples, the maximum value and the minimum observed values are recorded for each oxygen feed rate. The Table includes data for the wet well and force main discharge. The data for total sulfides and dissolved oxygen are plotted in Figure 13.

The effect of dissolved oxygen on sulfide levels is clearly shown by the plot of the data. There are several conditions indicated by the plot of these data that require additional comment. First, although dissolved sulfides were completely oxidized at all oxygen feed rates studied, it was not possible to reduce total sulfides to zero. Sulfides, in the form of metallic sulfides, would appear as total sulfides, but are not dissolved sulfides. In the insoluble metallic sulfide form, they are not involved in the undesirable reactions associated with dissolved sulfides. This clearly points out the necessity of measuring both dissolved and total sulfides. The temperature during the test period was near the maximum observed for the sewage. This high temperature increased the oxygen demand and

Table 6

OPTIMIZATION OF OXYGEN INJECTION

Railroad Ave. - Thomas Blvd. Pump Station - Force Main
[Test Period: June 23 - September 9, 1969]

Parameter	Sampling Point	Oxygen Injection Rates (cfm)						
		0	2.0	3.0	4.0	4.5	5.0	6.0
Temperature (°C)	WW	Ave. 29	30	30	30	30	30	30
		Max. 29	31	31	30.5	31	31	32
		Min. 28	29	30	29	30	29	29
	D	29	30	31	30	30	31	30
		29	31	31	31	31	33	33
		28	29	30	28	29	29	30
pH	WW	7.0	7.2	7.1	7.0	7.0	6.9	6.7
		7.1	7.2	7.1	7.2	7.0	7.2	7.3
		6.9	7.1	7.0	6.6	6.7	6.8	5.9
	D	7.1	7.1	7.0	7.0	7.1	6.9	6.8
		7.1	7.2	7.2	7.5	7.3	7.2	7.3
		7.0	6.9	6.9	6.6	6.8	6.5	5.6
Total Sulfides (mg/l)	WW	0.5	1.5	1.7	1.0	0.8	1.9	2.0
		1.8	2.1	2.1	1.8	0.9	3.3	3.0
		0.3	1.0	1.3	1.0	0.3	0.6	0.5
	D	1.2	0.1	0.1	0.2	0.2	0.1	0.1
		2.1	0.3	0.2	2.5	1.3	0.3	0.2
		0.9	0	trace	0	0	0	0
Dissolved Sulfides (mg/l)	WW	0.4	0.9	0.8	0.7	0.5	1.3	1.2
		1.1	1.4	0.9	1.6	0.6	2.1	2.0
		0.2	0.6	0	0.1	0.3	0.4	0.3
	D	1.1	0	0	0.1	0	0	0
		2.1	0.2	trace	2.0	1.3	0.2	0
		0.3	0	0	0	0	0	0
Dissolved Oxygen (mg/l)	WW	-	0.4	-	0.6	-	-	-
		-	0.4	-	0.6	-	-	-
		-	0.4	-	0.6	-	-	-
	D	-	1.1	2.1	3.5	-	2.0	2.3
		-	3.2	3.8	12.0	-	3.2	3.2
		-	0	0.8	0	-	0.6	1.0
Biochemical Oxygen Demand (mg/l)	WW	203	269	264	202	173	180	326
		372	332	310	250	337	270	436
		102	215	232	67	90	30	174
	D	282	252	272	189	189	231	312
		350	353	302	343	342	510	508
		170	209	250	55	49	30	174
Chemical Oxygen Demand (mg/l)	WW	487	417	428	388	480	404	740
		602	527	508	480	594	557	1680
		217	278	381	126	408	148	254
	D	527	412	441	382	480	437	597
		578	604	627	712	608	895	2070
		467	282	353	59	283	138	110

*WW - Wet Well, D - Force Main Discharge

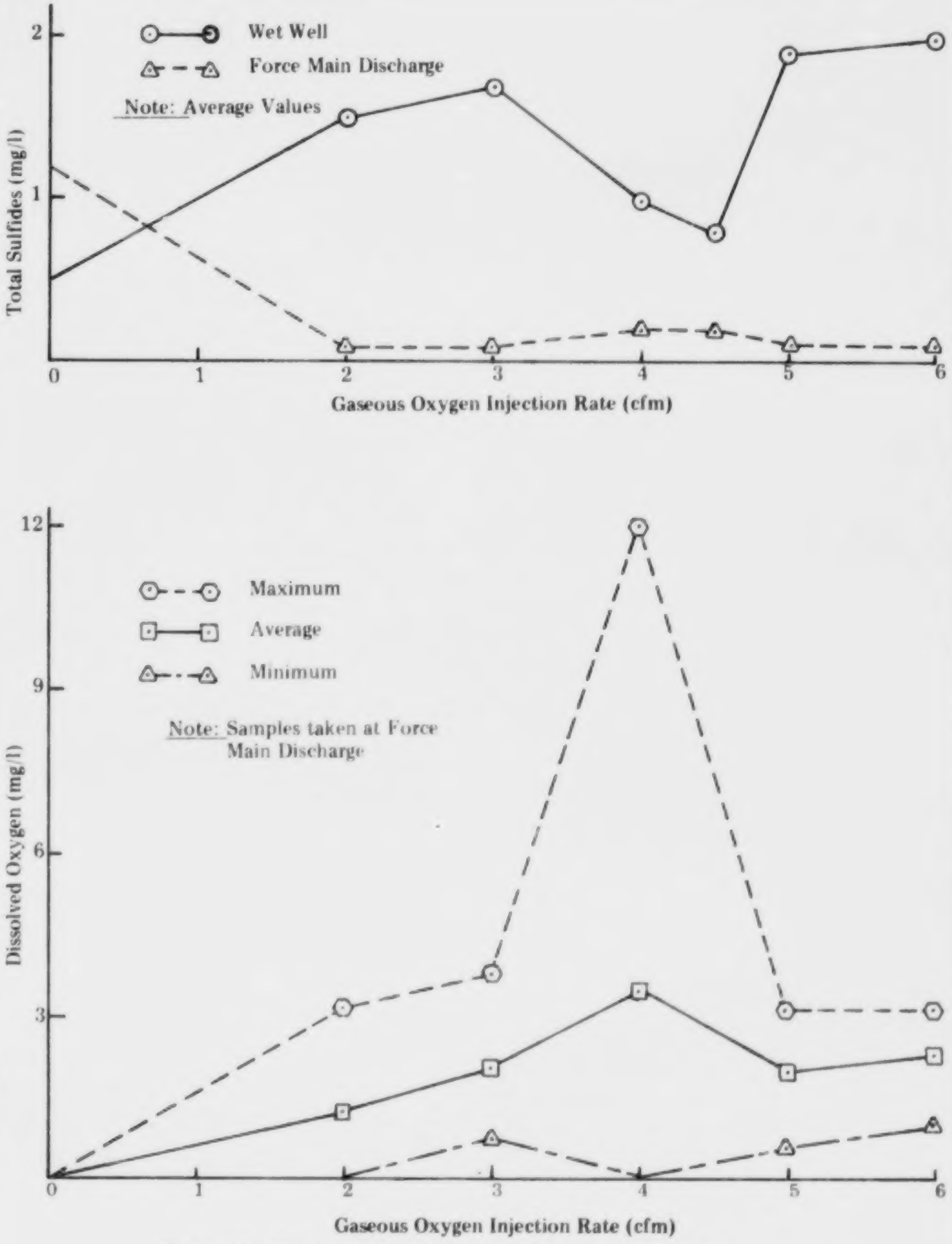


Figure 13. Total Sulfide and Dissolved Oxygen Levels During Oxygen Injection Optimization Study - Railroad Ave.-Thomas Blvd. Pump Station

sulfide generating potential of the sewage. The ability to control sulfides under the most severe conditions meant that control could be effectuated under all other conditions observed.

The injection of pure oxygen into a liquid stream should allow almost any level of saturation or super-saturation to be attained, and the magnitude of dissolved oxygen in the force main discharge increased with increased feed rates; however saturation values were equalled or exceeded for only one oxygen feed rate during the study period. This was for only one individual sample and not an average condition. It should also be pointed out that the highest average residual dissolved oxygen level was also measured at this rate and it represented only 46 percent of saturation. However, oxygen data at this point cannot be considered as an optimal value, because other parameters indicated a much weaker sewage during the test period.

The optimum feed injection rate for dissolved oxygen residual was four cfm, an oxygen:water ratio of 2.48 percent. Observations of the force main discharge provides in part an answer to this condition. At lower oxygen feed rates, the discharge from the force main was smooth and undisturbed. At the higher feed rates, the flow was highly turbulent. The turbulence was caused by the release of large air (oxygen) bubbles. This would imply that the oxygen either degases or collects into bubbles after being initially dispersed and failing to dissolve. After bubbles form at the crown, they are moved downstream where they are released to the atmosphere at the discharge point.

BOD and COD tests were performed in conjunction with the optimization study. As seen in Table 6, the data were erratic and inconclusive.

Air Injection

Air injection at the Railroad Ave.-Thomas Blvd. Pump Station began in September, 1969 and has operated continuously until the present time. Optimization studies began September, 1969 and continued to August, 1970. The air feed was varied from zero to 100 cfm. At the completion of each series of tests at a fixed air injection rate, the feed rate was changed and the system permitted to adjust before conducting additional tests.

The test data obtained for the selected parameters are given in Table 7. The two prime parameters, total sulfides and dissolved oxygen, are plotted in Figure 14. Based on the sulfide plot, it would appear that the optimum feed would lie between 36 and 60 cfm for the 16 inch diameter force main. This would represent an air:water ratio of 17.39 to 37.50 percent. The data also indicates a possible second optimum point to occur at higher feed rates. However, this should be viewed with caution. At the air feed of 66 cfm, the BOD was almost twice the value as that at 60 cfm, indicating a higher potential for sulfide generation during the test period. The data obtained for dissolved oxygen exhibited changes that corresponded in general to the changes in sulfides. Dissolved oxygen residuals were high when sulfide levels were low and low when sulfide levels were high.

Table 7. OPTIMIZATION OF AIR INJECTION

Railroad Ave.-Thomas Blvd. Pump Station – Force Main
[Test Period Sept. 25, 1969-Aug. 19, 1970]

			Air Injection Rate (cfm)									
PARAMETER	Sampling Point		0	12	24	33	36	48	60	66	100**	100
Temperature (°C)	WW*	Ave.	28	30	29	27	30	30	30	27	29	24
		Max.	29	31	30	27	31	30	31	27	29	31
		Min.	27	27	29	27	26	29	29	27	29	16
	D		26	30	28	26	29	30	30	26	27	24
			26	30	29	26	30	31	30	28	27	21
			26	29	27.5	26	28.5	29	29	26	27	16
pH	WW		7.0	6.9	6.7	6.8	6.7	6.8	6.9	6.8	6.5	7.1
			7.0	7.1	6.9	6.8	7.0	6.9	7.2	6.8	6.6	7.5
			7.0	6.7	6.6	6.7	6.4	6.7	6.7	6.8	6.4	6.7
	D		7.0	6.9	6.9	6.8	7.0	6.9	7.1	6.9	6.6	7.3
			7.0	7.2	7.0	6.8	7.8	7.5	7.4	7.0	6.7	9.6
			7.0	6.7	6.8	6.8	6.3	6.6	6.9	6.8	6.5	6.6
Total Sulfides (mg/l)	WW		1.4	1.4	1.7	1.4	1.4	1.4	1.3	2.0	2.0	1.0
			1.9	2.0	2.4	2.2	2.4	2.0	2.0	2.7	2.0	1.8
			1.2	0.6	1.4	0.9	0.4	0.8	0.3	1.5	1.5	0
	D		2.3	0.7	2.1	2.7	0.6	0.3	0.1	1.5	0.5	0.1
			3.0	2.5	3.4	5.0	2.4	1.6	0.8	2.1	0.6	1.4
			1.5	0.1	0.4	1.8	0	0	0	1.2	trace	0
Dissolved Sulfides (mg/l)	WW		1.1	1.2	1.5	1.2	1.2	1.2	1.1	1.8	1.6	0.8
			1.5	2.0	2.2	2.2	2.2	1.8	1.8	2.0	1.6	1.8
			0.7	0.5	1.2	0.9	0.3	0.7	0.2	1.4	1.6	0
	D		2.0	0.5	1.6	2.3	0.5	0.2	0	1.0	0.3	0
			3.0	2.0	3.0	3.5	1.9	1.0	0.6	1.7	0.6	0.2
			1.3	0	0	1.8	0	0	0.1	0.6	trace	0
Dissolved Oxygen (mg/l)	WW		0	0	0	0	0	0	0	0	0.9	0.4
			0	0	0	0	0	0	0	0	0.9	2.2
			0	0	0	0	0	0	0	0	0.9	0
	D		0	0.2	0	0	0.4	0.7	0.7	0	2.4	2.1
			0	1.0	0.2	0	2.0	1.8	1.8	0	2.8	6.0
			0	0	0	0	0	0	0	0	2.0	0
Biochemical Oxygen Demand (mg/l)	WW		269	116	185	294	133	181	156	303	227	261
			278	300	252	343	210	310	210	329	280	466
			253	80	156	269	102	95	105	260	180	132
	D		251	136	183	251	148	171	142	280	173	271
			291	350	234	269	276	228	300	287	260	495
			186	90	150	242	90	75	95	265	110	120
Chemical Oxygen Demand (mg/l)	WW		472	543	449	446	553	737	533	485	435	522
			496	726	625	463	890	1288	614	542	458	1122
			445	449	223	438	372	494	413	445	415	314
	D		500	600	493	503	590	192	393	539	502	610
			511	722	610	524	728	1234	913	627	527	1000
			480	464	402	491	435	419	430	472	481	282

* WW - Wet Well, D - Force Main Discharge

** Aerated Sewage recirculated back into wet well

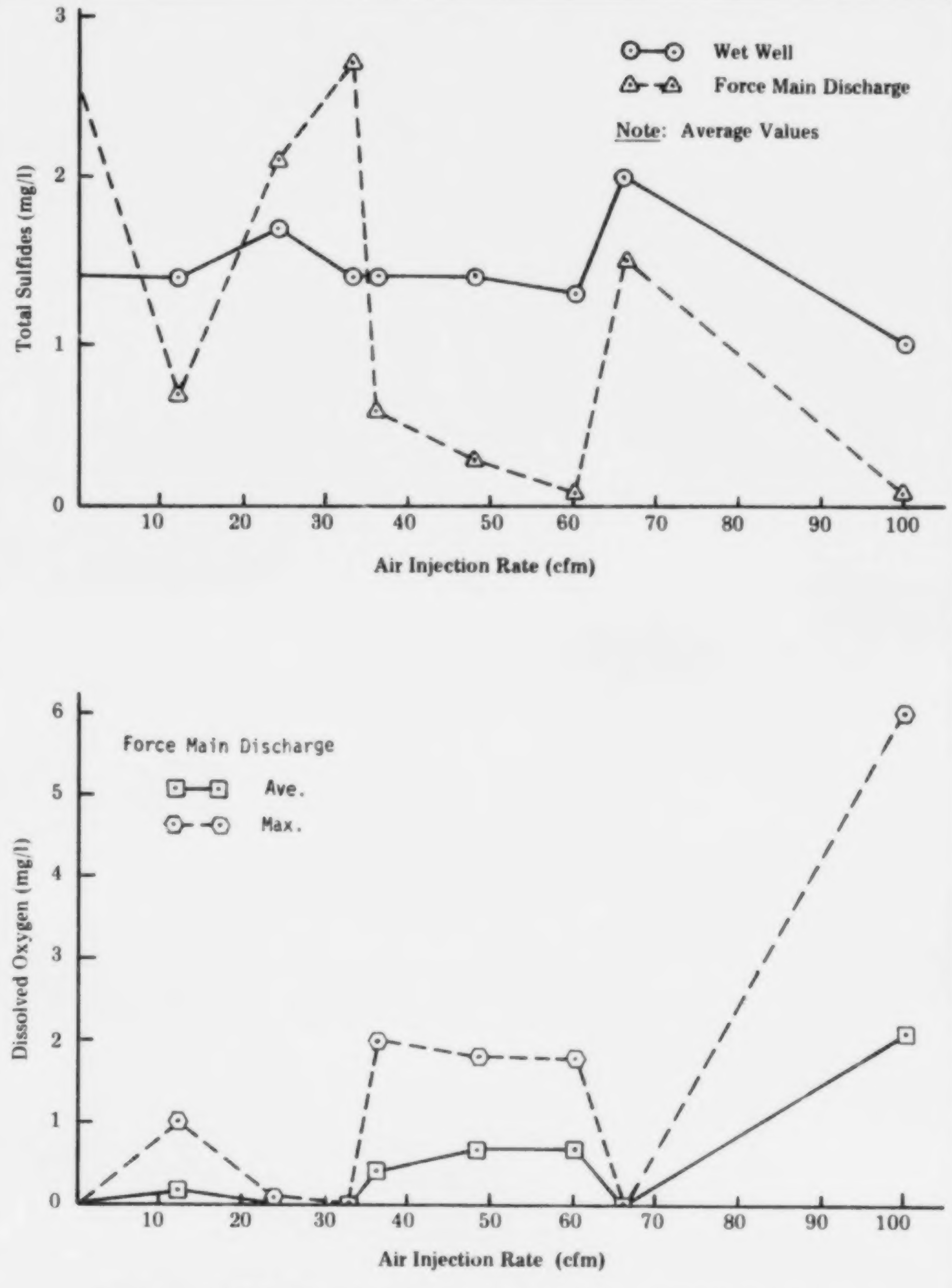


Figure 14. Total Sulfide and Dissolved Oxygen Levels during Air Injection Optimization Study - Railroad Ave.-Thomas Blvd. Pump Station

Consideration of optimum air flow rates must include the effects on the hydraulics of the system. This was not a consideration in the original project and no provisions were made for accurate flow measurements or evaluation of head losses for the various air rates. Attempts were made to predict pumping rates from wet well levels. However, the large variations in the levels and their failure to follow a consistent pattern made it necessary to abandon this method. Considering the failure to adequately evaluate the system hydraulics, the use of air flow rates should preempt the use of air:water ratios.

The discharge of the force main at the junction box cycled between smooth flow and highly turbulent flow. The periods of high turbulence were characterized by splashing and foaming accompanied by the sound of escaping air. As the air flow rate was increased, the magnitude and frequency of turbulence increased. This would indicate that the air collects at the crown of the pipe and is carried downstream as bubbles. An air flow rate where there was complete separation of air and sewage did not occur.

Lakeshore Interceptor

The evaluation of changes in sulfides and dissolved oxygen in the gravity portion of the Lakeshore System could not be correlated with specific air or oxygen feed rates. There were several factors that contributed to this. Foremost was the inability to measure flow rates and the lack of facilities for continuous sampling.

The data collected from July, 1969 to February, 1970 were grouped according to temperature. These data are shown in Table 8. The average sulfide levels are plotted in Figure 15 for each temperature grouping. The average total sulfide levels entering the gravity system for the selected time periods could not be evaluated due to the system operation. Considering the previously reported data on sulfide levels from the three stations, it could be assumed that the weighted average would have been low with periodic slugs of higher concentration.

The plotted data indicated an increase in sulfide levels at each downstream sampling point and for all temperatures with only two exceptions noted. As mentioned in the earlier discussion along this line, significant sludge deposits were present. An analysis of this sludge revealed sulfide concentrations of 80 mg/l. Considering these facts it is very possible that the sewage flowing over this material could leach sulfides from the debris as it moves downstream. This continual leaching of the sulfides plus generation in the slime layer would react with residual oxygen or oxygen from reaeration in the line downstream. Dissolved oxygen was found in only trace amounts for individual samples, and never observed consistently for any period of time.

STILLWELL SYSTEM

The system as defined for the study has one lift station and a long gravity

TABLE 8

SEWAGE CHARACTERISTICS

Lakeshore Interceptor - Oxygen Injection at Both Grannis Avenue and Railroad Ave. - Thomas Blvd. Pump Stations

Sampling Point	Test Period	PARAMETER *					
		Temp. (°C)	pH	Total Sulfides (mg/l)	Dissolved Sulfides (mg/l)	Dissolved Oxygen (mg/l)	BOD (mg/l)
Lakeshore Drive & Waco Ave.	August 1969	31.5	7.0	0.4	0.2	0	292
	September 1969	30.5	7.6	1.5	1.4	0	411
	Oct.-Nov. 1969	24.0	7.3	0.3	0.2	0	246
	Jan.-Feb. 1970	18.0	7.4	trace	0	0.3	-
Lakeshore Drive & Stillwell Blvd.	August 1969	31.5	7.4	1.8	1.5	0	356
	September 1969	30.5	7.4	3.4	3.2	0	366
	Oct.-Nov. 1969	26.0	7.5	2.5	1.8	0	307
	December 1969 - April 1970	19.0	7.7	0.6	0.3	trace	187
Lake Charles Lift Station	August 1969	31.5	7.0	2.5	2.1	0	313
	September 1969	30.0	7.2	2.6	2.3	0	371
	Oct.-Nov. 1969	24.0	7.1	1.3	0.8	0	197
	December 1969 - February 1970	18.0	6.8	0.8	0.5	-	203

*** Average values**

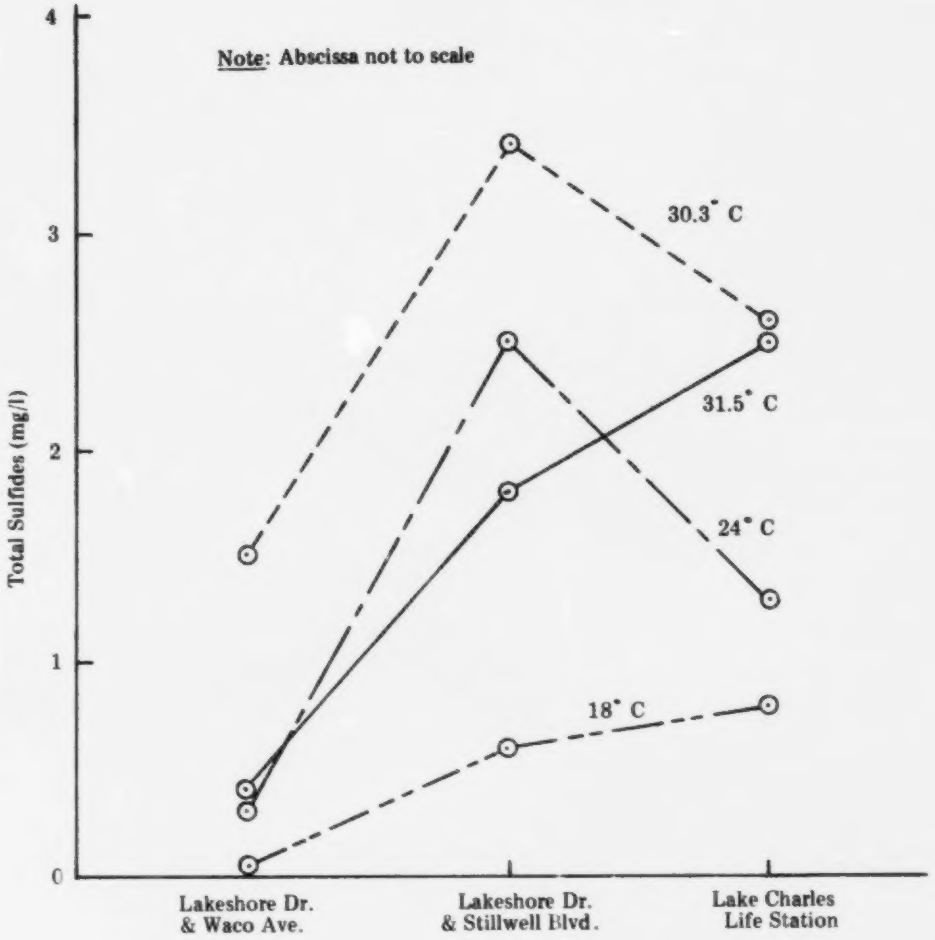


Figure 15. Sulfide levels, Lakeshore Interceptor, by temperature grouping

line. The gravity system upstream from the lift station serves a large area in which the gravity lines are very long with flat slopes. The lift station, identified as the 19th Street-Stillwell Boulevard (also Alligator Bayou), has a dry weather flow capacity of 2400 gpm and a 16 inch diameter force main approximately 600 feet in length. The force main discharges into a 24 inch diameter gravity sewer which transports the sewage to the Lake Charles Lift Station. The gravity sewer changes to 30 inch diameter pipe 2700 feet upstream of the wet well. The lift station and gravity line were constructed in 1951. Details of the system are shown in Figure 16.

Strong odors have always been associated with the wet well of this lift station, however, complaints have been minimized due to its location. The most persistent area of complaints has been in the vicinity of the manhole where the force main discharges. Sections of the downstream gravity line have failed due to deterioration. The pipe that has not been replaced was found to be in critical condition with failure possible at any time.

Sulfide Levels

Data collection was started in June, 1969 to evaluate system sulfide levels. The amount of base data collected was limited as this was one of the first sites to receive oxygen injection. It was necessary, because of operating conditions, to change sampling locations during the study to obtain samples unaffected by oxygen injection. The amount of sulfide data on untreated sewage at the lift station is more complete than for the gravity system.

Lift Station - Wet Well

The sampling points are located in Figure 16. Initially, all samples were taken from the wet well for evaluation of sewage characteristics. After recirculation of treated sewage was started, it was necessary to sample the gravity line entering the wet well to ascertain characteristics of the untreated sewage. The data are shown in Table 9 for sewage characteristics from manholes immediately upstream of the station or from the wet well. Additionally, the sulfide levels at the point of discharge from the force main are shown.

The sulfide levels entering the wet well and in the wet well are shown to be near the same level as the force main discharge. The major problem of the station was the release of hydrogen sulfide gas due to turbulence in the wet well and at the discharge manhole. The short force main did not serve as a major sulfide generator.

Gravity Line

The gravity line was observed to have large quanities of debris deposited in the pipe. This hampered sampling of the line, particularily during the low flow periods. Data collected for the gravity system are shown in Table 10. The sulfide level of the sewage from the force main discharge is shown to increase downstream with the exception of the last station. There are changes in direction which create turbulence prior to this sampling

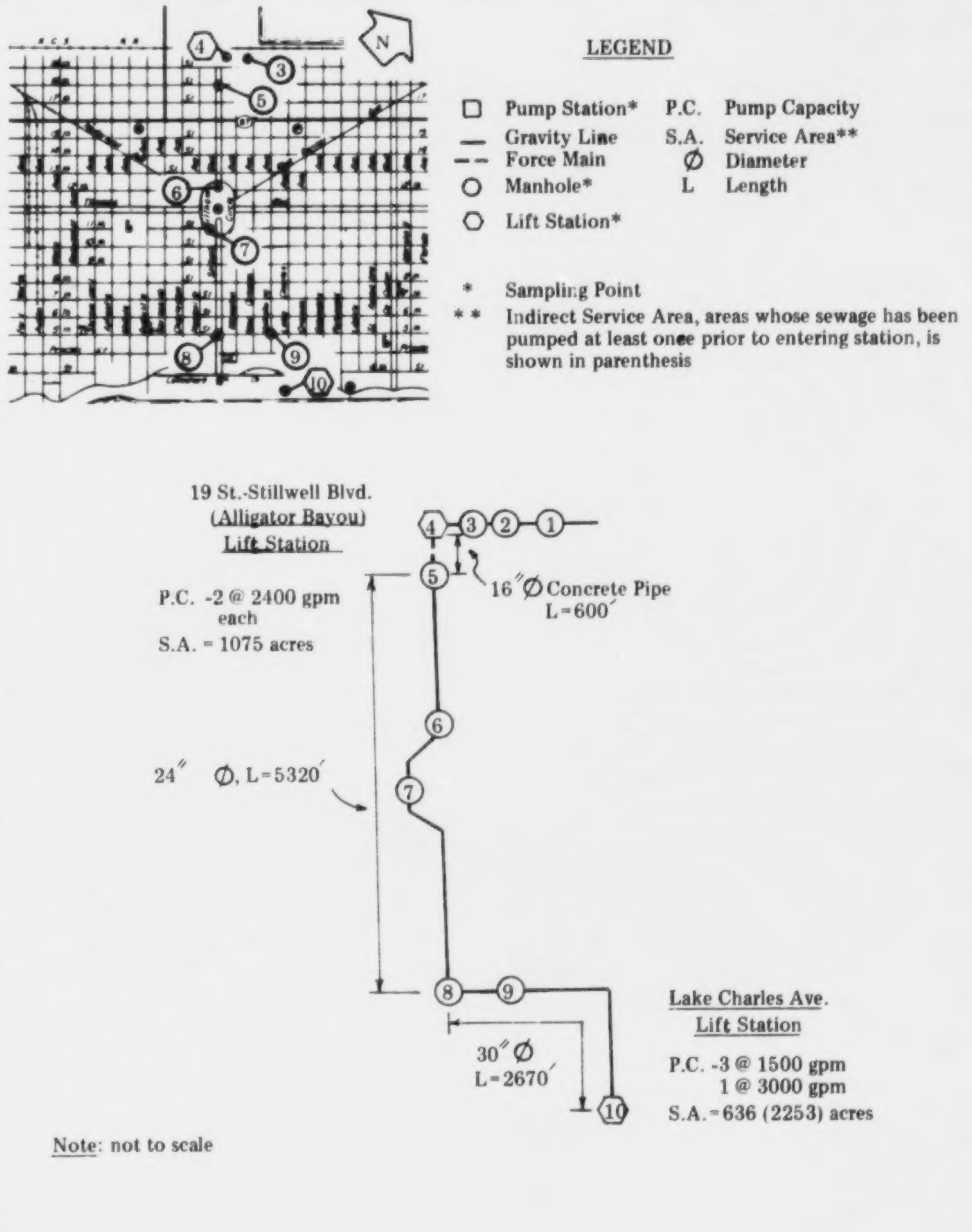

N
LEGEND
☐ Pump Station*
— Gravity Line
- - Force Main
○ Manhole*
⬡ Lift Station*
P.C. Pump Capacity
S.A. Service Area**
Ø Diameter
L Length
* Sampling Point
** Indirect Service Area, areas whose sewage has been pumped at least once prior to entering station, is shown in parenthesis
19 St.-Stillwell Blvd.
(Alligator Bayou)
Lift Station
P.C. -2 @ 2400 gpm each
S.A. = 1075 acres
16″Ø Concrete Pipe
L=600′
24″ Ø, L=5320′
30″Ø
L=2670′
Lake Charles Ave.
Lift Station
P.C. -3 @ 1500 gpm
1 @ 3000 gpm
S.A.=636 (2253) acres
1
2
3
4
5
6
7
8
9
10
Note: not to scale

Figure 16. Stillwell System

Table 9

SEWAGE CHARACTERISTICS

19th Street - Stillwell Blvd. Lift Station - Force Main

Sampling Point	Test Period	PARAMETER *					
		Temp. (°C)	pH	Total Sulfides (mg/l)	Dissolved Sulfides (mg/l)	BOD (mg/l)	COD (mg/l)
Manhole No. 1	Jan. - March, 1970	18.9	6.8	2.12	1.82	168	481
Manhole No. 2	Feb.-March, 1970	19.1	6.8	0.84	0.54	129	284
Wet Well	June-July, 1969	29.4	6.9	2.64	2.21	260	486
19th Street Manhole (Force Main Discharge)	June-July, 1969	29.9	6.8	2.59	1.97	176	412

Table 10

SEWAGE CHARACTERISTICS

Stillwell System

[Test Period: June 24 - July 7, 1969]

Sampling Point	PARAMETER*						
	Temp. (°C)	pH	Total Sulfides (mg/l)	Dissolved Sulfides (mg/l)	Dissolved Oxygen (mg/l)	BOD (mg/l)	COD (mg/l)
19th Street Lift Station Wet Well	29.5	7.0	2.6	2.2	0	260	486
19th Street Force Main Discharge	30.0	6.8	2.6	2.0	0	176	412
Gillham Circle Manhole No. 1	30.0	-	1.4	0.6	-	-	-
Gillham Circle Manhole No. 2	28.0	7.1	3.4	2.8	0	160	464
Stillwell Blvd. & 5th Avenue	27.5	7.2	4.2	2.9	0	160	427
Vickburg Avenue & 5th Avenue	28.0	6.5	2.4	1.4	0	143	378

* Average Values

point. This would permit the release of hydrogen sulfide thereby lowering the sulfide level. The pipe in this area has been severely damaged indicating the release of gases for a long period.

The increase in sulfide levels downstream would indicate that the gravity line serves as a sulfide generator. The sludge was sampled to determine if this material would have affected the test results if some of it was inadvertently included in the sample. Dewatered samples of the debris were placed in distilled water and the supernatent tested for sulfides. The sludge was found to contain sulfides as high as 80 mg/l. Thus, the increases in sulfides shown could have been influenced significantly if samples had included this material.

System Design & Operation

The high sulfide level entering the wet well of the lift station was the major problem at this site and not generation through the short force main. The downstream gravity line appeared to be a major generator of sulfides; however, this should not be considered conclusive due to sampling problems encountered with sludge deposits. These two conditions established criteria for control at this site: oxidation of existing sulfides and maintenance of residual dissolved oxygen in the sewage. The length of the force main was considered to be inadequate for air injection. However, the injection of pure oxygen was to be employed for the interim period prior to fabrication of a pressure tank, the preferred technique for sulfide control with air at this location.

Oxygen tanks (truck trailers) were moved to the site and necessary piping installed. Diffuser tubes in an expanded pipe section as shown in Figures 4 and 5 were to be used for gas entrainment. A solenoid valve was used in conjunction with a timer to control the oxygen feed. The valve was set to open 10 seconds after the pump started to assure that oxygen would be injected into a liquid stream. The oxygen injection system was operated and tested from June, 1969 until September, 1969. The data collected for this test period are shown in Table 11.

The data for sulfides and oxygen at the various oxygen feed rates are plotted in Figure 17. A slight reduction in sulfides was obtained but they were not reduced to acceptable levels for the oxygen feed rates tested. The oxygen transfer was equally disappointing for the system. There was only one oxygen feed rate at which any significant amount of dissolved oxygen was found in the force main discharge. This would indicate that the optimum would occur at a feed rate in excess of the 10 cfm tested. Interpretation of this data at the higher feed rate should be viewed with caution, particularily in view of the failure to oxidize any significant amount of sulfides.

Observations of the force main discharge during the testing offer an explanation for the failure of the system to achieve a higher oxygen transfer. At all oxygen feed rates the force main discharge was characterized by a high degree of turbulence and foaming, the magnitude of which increased with increased feed rates. This was not observed when there was no oxygen feed. The flow could be described as a liquid carrying large bubbles of oxygen down-

Table 11

OPTIMIZATION OF OXYGEN INJECTION

19th Street Lift Station - Force Main

[Test Period June 24 - Sept. 12, 1969]

PARAMETER	Sampling Point		Oxygen Injection Rate (cfm) 0	4.0	6.0	7.75	9.75	10.0
Temperature (°C)	WW	Ave.	30	29	30	29	30	30
		Max.	32	29	31	31	30	32
		Min.	28	29	29	24	30	29
	D		30	32	31	29	29	30
			31	33	34	31	29	32
			27	29	28	28	29	28
pH	WW		7.0	7.2	6.9	7.1	7.1	6.9
			7.2	7.2	7.0	7.1	7.1	
			6.9	7.2	6.8	7.1	7.1	
	D		6.9	7.0	7.0	6.9	7.1	7.2
			7.1	7.2	7.2	7.0	7.1	7.2
			6.4	6.9	6.8	6.8	7.1	6.9
Total Sulfides (mg/l)	WW		1.6	2.2	3.8	1.7	2.0	3.2
			2.0	2.2	5.0	2.4	2.0	4.1
			1.0	2.2	2.0	0.2	2.0	2.2
	D		2.5	2.0	3.1	1.6	1.7	2.1
			2.6	3.4	3.8	2.9	1.7	5.7
			0.8	0.4	0.9	0	1.7	0.7
Dissolved Sulfides (mg/l)	WW		1.6	1.8	3.4	1.6	2.0	2.4
			2.0	1.8	4.8	2.2	2.0	3.3
			0.8	1.8	2.0	0.2	2.0	1.5
	D		2.0	1.4	2.3	1.3	0.9	1.3
			2.2	3.3	3.7	2.7	0.9	2.6
			0.2	0.4	0.6	0	0.9	0.5
Dissolved Oxygen (mg/l)	WW		0	-	-	-	-	-
			0	-	-	-	-	-
			0	-	-	-	-	-
	D		0	0.2	0.3	-	-	1.4
			0	0.2	1.8	-	-	6.1
			0	0	0	-	-	0
Biochemical Oxygen (mg/l)	WW		177	-	388	188	194	-
			186	-	500	323	194	-
			164	-	101	156	194	-
	D		176	269	282	130	160	-
			200	385	445	182	160	-
			141	192	85	60	160	-
Chemical Oxygen Demand (mg/l)	WW		415	557	440	604	846	681
			522	557	846	897	846	1590
			214	557	300	251	846	334
	D		412	429	454	445	697	508
			557	605	636	661	697	676
			231	207	223	234	697	427

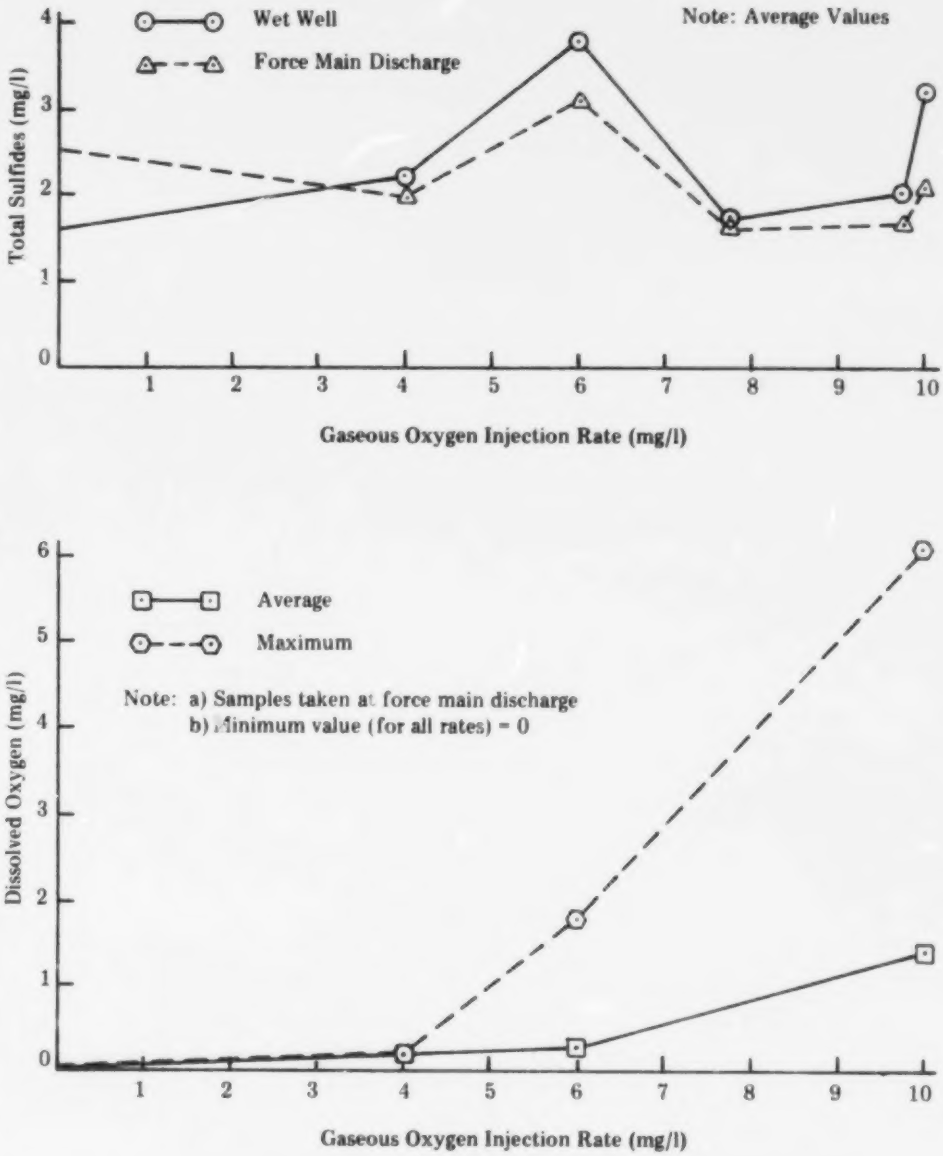


Figure 17. Total Sulfide and Dissolved Oxygen Levels During Gaseous Oxygen Injection Optimization Study - 19th Street - Stillwell Blvd. Lift Station

stream with the bubbles erupting at the point of discharge. Samples taken at the force main discharge and placed in glass containers had the appearance of boiling water for a few minutes due to the degassing of the entrained oxygen bubbles and not the evolution of dissolved oxygen. Testing for sulfides and dissolved oxygen was performed after degassing was completed. For practical purposes, a two phase (liquid - gas) flow regime existed which separated immediately when a free surface was created in the gravity line. The result, as indicated by the data, was to add oxygen to the sewer atmosphere and not increase the dissolved oxygen content of the sewage or oxidize sulfides.

The installation of the pressure tank was completed and placed in operation during November, 1969. The original installation called for a variable detention time of 17 to 30 minutes and operating pressures of from one to two atmospheres. Air to water ratios could be varied from zero to 35 percent. Details of the pressure tank are shown in Figure 6. The air was injected through diffusers installed perpendicular to the tank wall at two levels and equally spaced around the tank periphery.

The pressure tank was designed to handle the low flow of the station under normal condition, i.e. no excessive infiltration, at a detention time of approximately 20 minutes. During the peak hourly flows, the pumps at the station would operate, by-passing the pressure tank and discharging directly into the gravity line. At the peak hourly flow, approximately 50 percent of the flow through the station is bypassed. This condition, based upon pump time evaluations, would occur approximately nine periods per day. The total sewage bypassed would represent approximately 30 percent of the total flow through the station.

Sampling began in November, 1969 with the start-up of the pressure tank and continued until February, 1970. During this initial start-up period for the equipment, numerous problems were encountered which prohibited a continuous sampling program from being carried out. Most of the problems experienced were mechanical problems with equipment and not performance problems with one exception. There was a significant decrease in the quality of the effluent from the tank. The dissolved oxygen level began to decrease and the sulfide content began to increase. The tank was inspected and a solids buildup was found in the bottom of the tank. A drain line was installed from the bottom of the tank that would permit either continuous or intermittent draining of the tank back to the wet well. Continuous recirculation that returned an oxygen enriched stream to the wet well appeared to offer the best operational characteristics.

During March, 1970, a twenty-hour sampling program was conducted to cover the flow ranges and variation in sewage characteristics. The data collected during this period are shown in Table 12. The average sulfide and dissolved oxygen levels are presented in Figure 18. A reduction in total sulfides of 94 percent is shown across the system; however the effect of recirculation is significant with a reduction of 74 percent demonstrated. The important factor is that both total and dissolved sulfides in the wet well were below the recognized level for deterioration due to sulfides. The dissolved oxygen leaving the pressure tank was 67 percent of saturation while the force main discharge was 51 percent of saturation. Thus, a loss of dissolved

Table 12
SEWAGE CHARACTERISTICS

Pressure Tank Test Program
19 Street - Stillwell Blvd. Lift Station - Force Main
20-Hour Sampling Program

		Sampling Point			
PARAMETER	Sampling Period	Manhole at New Orleans	19th Street L.S. Wet Well	Pressure Tank Effluent Line	19th St. Force Main Discharge
Composite Temperature (°C)	1 *	19	20	20	19
	2	19	19	19	19
	3	19	19	19	19
	4	19	19	19	18
Composite pH	1	6.7	6.9	6.9	6.8
	2	6.8	6.9	7.9	6.8
	3	6.8	6.9	7.2	6.9
	4	6.7	6.8	6.8	7.0
Average Total Sulfides (mg/l)	1	2.5	0.8	0.4	0
	2	1.9	0.7	0.4	0.4
	3	2.8	0.5	0.3	0.1
	4	1.9	0.4	0.1	0
Average Dissolved Sulfides (mg/l)	1	2.4	0.6	0.3	0
	2	1.5	0.6	0.3	0
	3	2.4	0.4	0.2	0
	4	1.9	0.3	0.1	0
Average Dissolved Oxygen (mg/l)	1	0	1.0	6.4	4.5
	2	0	1.8	5.7	4.2
	3	0	2.8	6.4	5.3
	4	0	2.7	6.7	5.2
Composite BOD (unfiltered) (mg/l)	1	270	270	300	325
	2	195	185	95	130
	3	165	135	150	145
	4	130	140	135	115
Composite BOD (filtered) (mg/l)	1	205	225	210	225
	2	135	160	105	95
	3	125	120	125	115
	4	120	95	100	85
Composite COD (mg/l)	1	613	513	498	632
	2	578	528	410	494
	3	362	419	370	400
	4	392	426	355	373
Composite Suspended Solids (mg/l)	1	167	220	180	280
	2	97	110	147	123
	3	37	67	50	67
	4	130	157	133	300

* 1 - March 26, 1970, 1:00-5:00 p.m.
2 - March 26, 1970, 6:00-10:00 p.m.
3 - March 27, 1970, 12:00-4:00 a.m.
4 - March 27, 1970, 6:00-10:00 a.m.

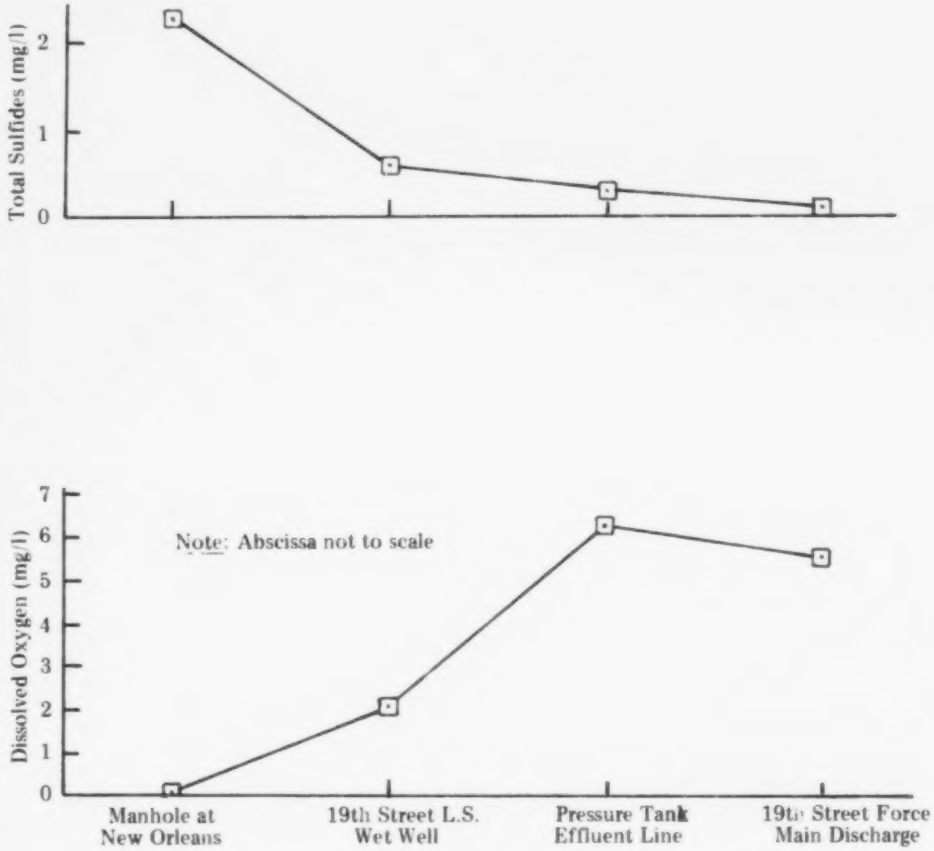


Figure 18. Average Total Sulfide and Dissolved Oxygen Levels during 20-hour sampling program evaluating pressure tank - 19th Street - Stillwell Blvd. Lift Station

oxygen occurred in the force main and at the discharge manhole. Perhaps the most important aspect of the twenty hour sampling program is the high dissolved oxygen level found in the wet well.

The initial period of testing indicated a reduction in BOD and this period of concentrated testing gave an excellent opportunity to evaluate changes. A reduction in BOD would indicate the development of a biological floc and for this reason a biochemical oxygen demand test was run on filtered and unfiltered samples. The unfiltered samples for all sample locations averaged 28 percent greater than filtered samples. A reduction was shown in the BOD across the system for both filtered and unfiltered samples. Suspended solids at all locations increased over the raw solids indicating the development of a biological floc. The maintenance of a residual dissolved oxygen level in the wet well could contribute significantly to this floc development.

Sampling was continued at the installation from March, 1970 until November, 1970. The sampling during this period was conducted at various times of the day. The sewage characteristics observed for the period are shown in Table 13.

Sulfide levels were reduced by 90 percent to a concentration of 0.3 and 0.1 for total and dissolved sulfides respectively. The dissolved oxygen level of the pressure tank effluent averaged 61 percent of saturation dropping to 28 percent at the discharge manhole. The pressure tank demonstrated a 16 percent reduction of the wet well influent BOD while the force main discharge had only a 13 percent reduction. It is significant to note that for the period, the COD of the wet well, pressure tank discharge and force main discharge were essentially unchanged.

SMITH-YOUNG SYSTEM

The Smith-Young System consists of a single pump station that discharges into a gravity sewer that connects with the Lakeshore Interceptor near the Mainline Pump Station. Dry weather pumping capacity is 350 gpm. The pump station serves 164 acres and the gravity sewer serves an additional 1800 acres between the pump station and the interceptor.

The force main, the longest in the Port Arthur Sewerage System, is 8 inches in diameter and 5,427 feet in length. The gravity sewer is 12,600 feet from the force main discharge to the Lakeshore Interceptor. The pipe diameter increases from 15 inches to 30 inches in diameter. Details of the system are shown in Figure 19. The profile of the force main is shown in Figure 20. The changes in slope up to the point where the force main goes under the drainage ditch proved to be a significant factor in the system operation.

Sulfide Levels

Since the construction of the pump station in 1956, odor problems and

Table 13

SEWAGE CHARACTERISTICS

Pressure Tank Test Program
19th Street - Stillwell Blvd. Lift Station - Force Main
[Test Period June 26 - Nov. 27, 1970]

Sampling Point Parameter	New Orleans manhole and manhole at trailor	19th Street L.S. Wet Well	Pressure Tank Effluent Line	19th Street Force Main Discharge
Temperature (°C)	Ave. 23.0	24	24	24
	Max. 29.0	30	30	29
	Min. 18.5	19	18	17
pH	6.8	6.8	7.0	6.9
	7.0	6.9	7.2	7.0
	6.6	6.6	6.6	6.6
Total Sulfides (mg/l)	4.3	1.5	0.4	0.3
	7.4	3.6	1.0	1.5
	1.1	0.3	0.1	0
Dissolved Sulfides (mg/l)	4.1	1.3	0.2	0.1
	6.9	3.0	0.5	0.8
	0.8	0.1	0.1	0
Dissolved Oxygen (mg/l)	0	1.0	5.2	2.4
	0	7.0	7.0	6.0
	0	0	2.4	0.2
Biochemical Oxygen Demand (mg/l)	209	174	175	181
	474	270	300	325
	100	120	80	72
Chemical Oxygen Demand (mg/l)	423	457	440	429
	651	528	660	623
	107	378	355	203

Note: A portion of the aerated sewage from the pressure tank was being recirculated back into the wet well

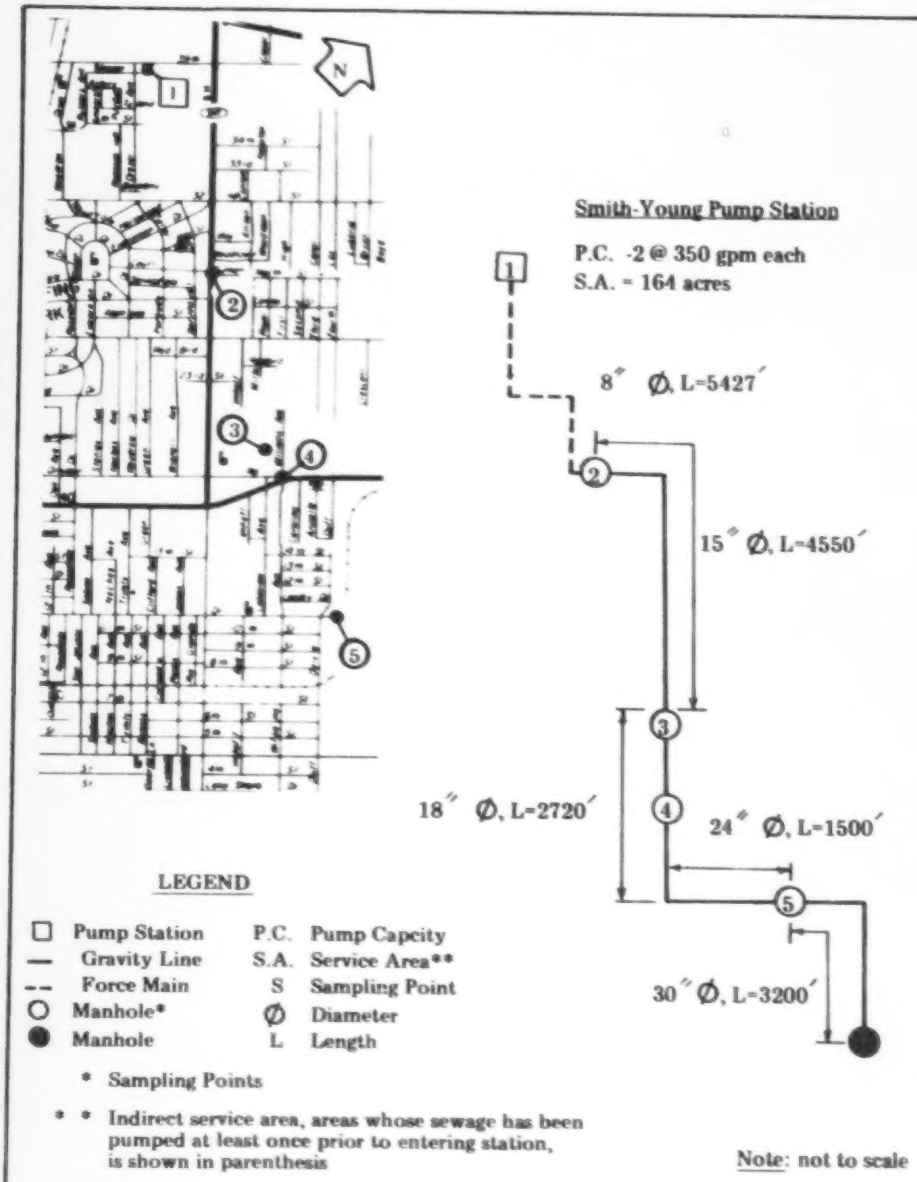

Smith-Young Pump Station
P.C. -2 @ 350 gpm each
S.A. = 164 acres
1
2
3
4
5
N
8" Ø, L=5427'
15" Ø, L=4550'
18" Ø, L=2720'
24" Ø, L=1500'
30" Ø, L=3200'
LEGEND
□ Pump Station
— Gravity Line
-- Force Main
○ Manhole*
● Manhole
P.C. Pump Capcity
S.A. Service Area**
S Sampling Point
Ø Diameter
L Length
* Sampling Points
* * Indirect service area, areas whose sewage has been pumped at least once prior to entering station, is shown in parenthesis
Note: not to scale

Figure 19. Smith-Young System

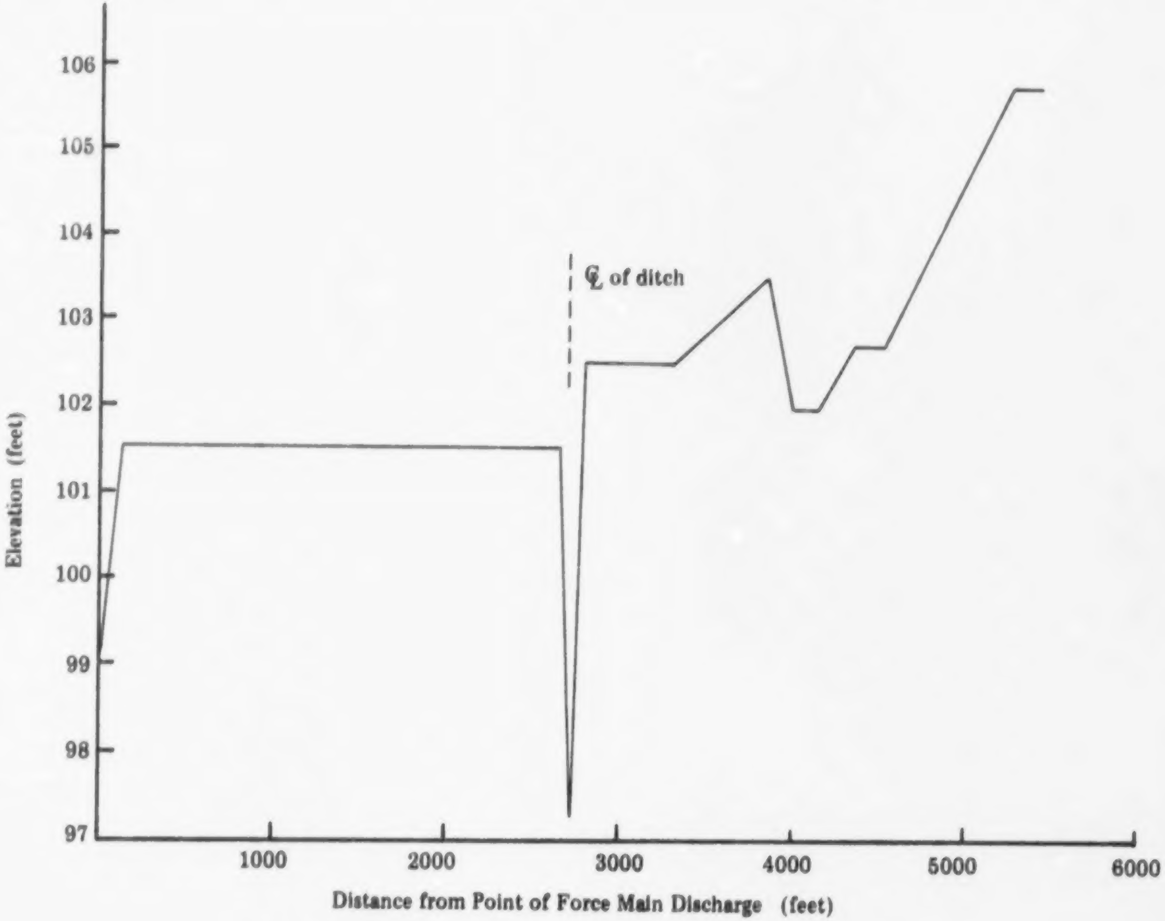


Figure 20. Profile of Smith-Young Force Main

deterioration have gradually intensified. The most severe odor problems have occurred at the point where the force main discharges into the gravity system (Sunken Court manhole). Large segments of the gravity system have failed with the most recent in December, 1971. The failure required the replacement of 800 feet of 15 inch diameter pipe.

Sewage characteristics were observed throughout the system from June until September, 1969. Sampling stations were established at the wet well, the force main discharge and points along the gravity line. The locations of these sampling stations are shown in Figure 19.

Smith-Young Pump Station (39th Street)

The sewage characteristics found in the wet well were not unusual for domestic sewage. Sulfide levels and BOD values were low. Extreme care was required in sampling the wet well as a thick mat of grease and other materials was found to be floating on the sewage. BOD values in excess of 800 mg/l were observed when this material was inadvertently picked up in the sample. The presence of this mat of grease can be explained by the fact that most of the houses in the subdivision have garbage grinders. It is also significant to note that sewage temperatures during this period averaged 29.5°C. Sulfide levels observed at the force main discharge were the highest observed for a sustained period of sampling. The increase in sulfide levels was the most dramatic and clearly establishes this as the principle sulfide generator of the system. The average increase in total sulfides was 9.75 mg/l and 9.0 mg/l of dissolved sulfides. Based on the average hydrogen ion concentration, approximately 40-50 percent of the sulfides were in the form of hydrogen sulfide gas. Data for the wet well and force main discharge are included in Table 14.

Gravity Line

The gravity line was sampled during the same period as the pump station. The data collected at the three sampling stations are included in Table 14 and sulfide data are plotted in Figure 21.

The plot of sulfides indicates a significant decrease in sulfides from the force main discharge to the downstream stations. Part of this decrease could be attributable to dilution with fresh sewage, infiltration or a combination of these. A second consideration would be the reduction in sulfides by the evolution of hydrogen sulfide gas by degassing at points of turbulence. Considering the history of odors and corrosion, the latter would appear to be the most reasonable assumption. This is further reinforced by the average hydrogen ion concentrations observed which establishes a relatively high percent of sulfides to be in the form of hydrogen sulfide gas. Considering the sulfide generation in the gravity line, which could not be determined the changes would have been even more radical.

System Design and Operation

The selection of air or oxygen gas injection at this station had to take several factors into consideration. The proximity of houses to the pump

Table 14

SEWAGE CHARACTERISTICS

Smith Young System

[Test Period June 21 - Sept. 12, 1969]

			PARAMETER				
Sampling Point	Temp. (°C)	pH	Total Sulfides (mg/l)	Dissolved Sulfides (mg/l)	Dissolved Oxygen (mg/l)	BOD (mg/l)	COD (mg/l)
Smith-Young	Ave. 29.5	6.8	0.9	0.8	0	184	876
Pump Station	Max. 31.0	7.0	1.8	1.6	1.0	190	1992
Wet Well	Min. 27.5	6.4	0.4	0.1	-	165	400
Smith-Young	29.1	6.9	10.7	9.8	0	266	366
Force Main	30.0	7.1	14.0	13.0	0.7	531	563
Discharge	27.5	6.8	3.0	2.1	0	140	222
Manhole behind	28.1	7.0	3.2	3.0	0	155	301
Thomas Jefferson	29.0	7.0	4.1	3.8	0	201	377
High School	27.5	6.9	2.2	2.0	0	89	247
Manhole at Intersec-	29.2	7.1	2.7	2.4	0	342	410
tion of Dryden Ave.	30.0	7.5	4.0	4.0	0	625	599
& Williams Street	28.5	7.0	1.6	1.3	0	218	311
Manhole at north-	29.3	7.1	0.7	0.6	0	283	409
east end of Lewis	32.0	7.2	1.3	1.3	1.2	563	590
Avenue	28.0	6.9	0	0	0	117	334

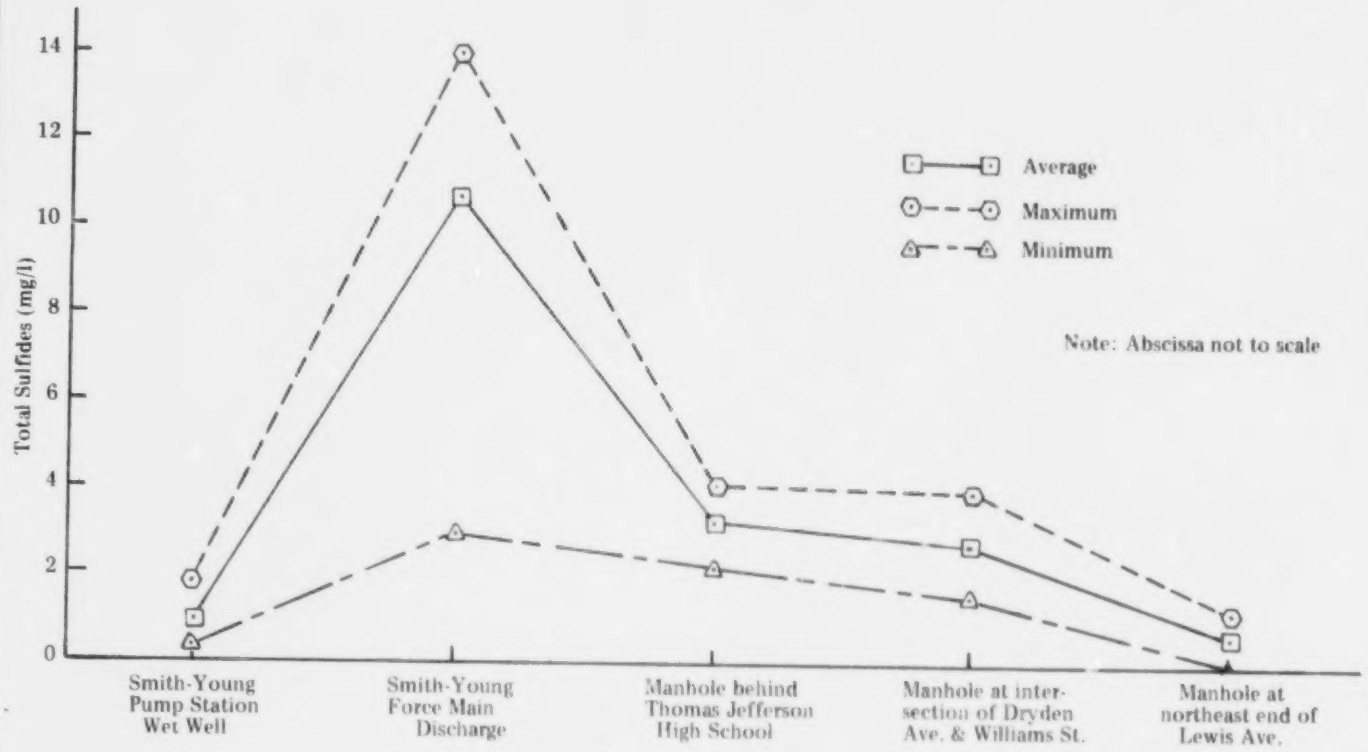


Figure 21. Total Sulfide Levels in the Smith-Young System

station imposed a noise constraint. The length of the line, coupled with the depression at the drainage ditch, indicated a potential air locking problem. Calculations indicated a velocity of from 2 to 3 fps, depending on roughness characteristics. The final decision was to use oxygen gas and to inject it without the use of diffusers. The oxygen was to be injected at three points, one in the bottom of the pipe and one in each of the bottom quadrants. The details of the original installation and later modifications are shown in Figure 22.

The installation of the equipment was completed and oxygen injection was started November 14, 1969. The initial oxygen feed rate of 10 cfm was set and a continuous monitoring program was scheduled for 48 hours. The principal goal was to see if the stripping of solids from the force main would occur as had been reported in the literature. The data collection was started and continued for approximately 24 hours. During this period, the sulfides in the discharge were low and the dissolved oxygen of the sewage was gradually increasing. The settleable solids at the discharge point were very erratic.

During this sample period, the length of the pump cycle was steadily increasing until a point was reached where the discharge was continuous. At the point of discharge, the force main was flowing less than one-half full and with a low velocity. The oxygen was turned off and a sample port on the force main before the oxygen injection point was opened. Oxygen was discharged from this line until sewage began to flow. The valve was closed and the oxygen was again injected at a rate of 10 cfm. In approximately two to four hours, the discharge was again severely restricted. After bleeding the oxygen from the line the second time, the pumps were permitted to operate without oxygen injection, and the pump cycle returned to normal. The oxygen feed rate was then set at four cfm and in approximately six hours, the previously described condition developed. The oxygen was once again bled from the system and an oxygen feed rate of one cfm was found to work without an undesirable effect on pumping rates. The data for this period of sampling were discarded due to flow conditions being atypical.

There are two possible explanations for failure of the system to operate. The most obvious one being that the depression in the force main resulted in the formation of a block and trapped oxygen on the upstream side. The second would be that due to the downward slope of the force main the oxygen was trapped in the vicinity of the pump station, the highest point in that section of pipe. Due to the ability to bleed off large volumes of oxygen at the pump station it would infer that the latter was the case.

Further testing revealed that at an oxygen feed rate of one cfm the system flow characteristics would not be seriously impeded. The system operated from December, 1969 until March, 1970 under this condition. Some degree of control was effectuated as the average total sulfides at the force main discharge was held to 2.2 mg/l. Considering the average temperature of 18.5^{o}C for the period, it was felt that this would not be adequate during periods of elevated temperature. The data obtained during this period are provided in Table 15.

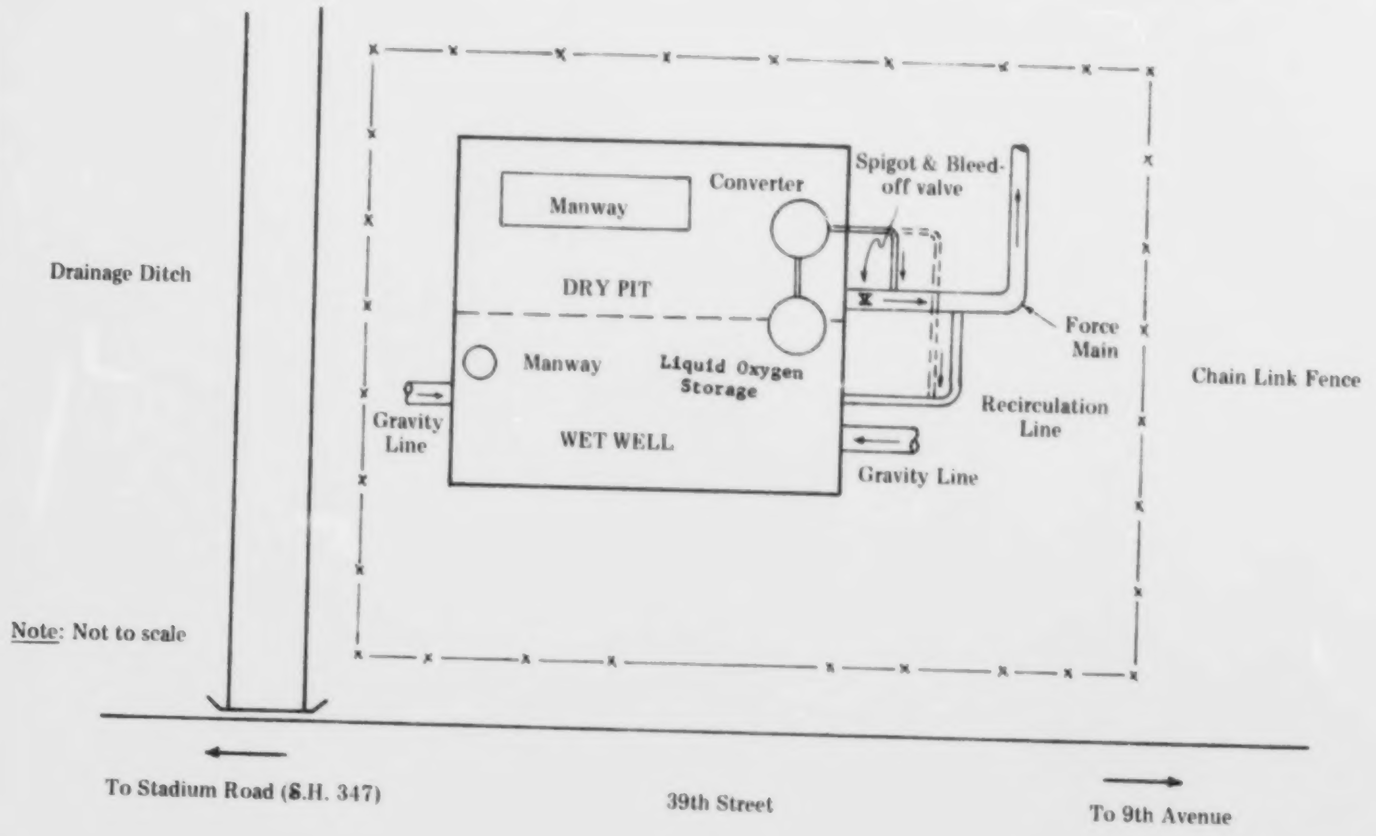

Drainage Ditch
Manway
Converter
Spigot & Bleed-off valve
DRY PIT
Force Main
Manway
Liquid Oxygen Storage
Chain Link Fence
Gravity Line
WET WELL
Recirculation Line
Gravity Line
Note: Not to scale
To Stadium Road (S.H. 347)
39th Street
To 9th Avenue

Figure 22. Smith-Young Pump Station

Table 15

SEWAGE CHARACTERISTICS

Smith Young Pump Station - Force Main
[Test Period Dec. 13, 1969 - March 6, 1970]

		PARAMETER				
Sampling Point	Temp. (°C)	pH	Total Sulfides (mg/l)	Dissolved Sulfides (mg/l)	Dissolved Oxygen (mg/l)	BOD (mg/l)
Wet Well	Ave. 17.6	6.8	1.2	1.0	0.4	296
	Max. 23.0	7.1	2.6	1.7	2.2	600
	Min. 12.0	5.1	0	0	0	130
Force Main Discharge	18.5	6.9	2.2	1.7	1.3	-
	20.0	7.2	5.0	4.4	9.0	-
	13.0	6.5	0	0	0	-

Note: O_2 (oxygen) injection rate of 1 cfm

A decision was made to provide a recirculation line to the wet well and inject oxygen into this line. Details are shown in Figure 22. The ability to achieve a high level of dissolved oxygen in sewage as it left the station was clearly demonstrated as the average value was 140 percent of saturation. Sulfide control was not demonstrated as the sulfide level at the force main discharge was greater than when the oxygen feed was directly into the line. Further consideration of the data reveals that the sulfides were controlled at a point approximately 3000 feet downstream from the pump and across the depression. The sulfides were then generated in the remaining 2500 feet to an undesirable level.

The ability to control sulfides and obtain a dissolved oxygen residual at the mid-point of the force main, a distance of approximately 2700 feet, was congruous with other locations. This indicated that the problem was one of system hydraulics and an excessive oxygen demand. The accumulation of oxygen gas in the crown of the pipe between the pump station and discharge was demonstrated by the large volumes of gas that could be released at the pump station. The force main in this section is relatively flat and after passing the depression, the force main has an overall positive slope to the final point of discharge shown in Figure 20. The force main configuration coupled with the apparent trapping of gas in the first section indicated a possible solution.

A jumper was installed across the depression to permit passage of the gas. Oxygen feed rates of one to four cfm continued to have adverse effects upon the system performance. This indicated that the oxygen gas was not being carried to the jumper. The oxygen feed was then increased to 10 cfm and oxygen gas was released at the discharge manhole. Under this condition the system hydraulics appeared to operate in a normal manner. Once the gas passed the point of depression it appeared to aid the flow condition in this section of the pipe indicating that the system will function properly provided the gas could be moved downstream of the depression. At the oxygen feed that this was achieved, the operation cost would be prohibitive.

The conditions observed for this system alluded to a means of solving the problem. Injection of air or gaseous oxygen immediately downstream of the depression would not appear to restrict normal flow conditions. Secondly, the remaining length of 2700 feet would provide adequate contact time to oxidize sulfides and prevent further generation of sulfides. The force main easement in this area is limited which imposes restrictions for the installation of gaseous oxygen or air compressor equipment.

PEAR RIDGE SYSTEM

The Pear Ridge System as defined for the study consists of three lift stations and a long gravity system. This system begins at the abandoned sewage treatment plant of the City of Pear Ridge. When the city abandoned wastewater treatment in favor of contracting with the City of Port Arthur for this service, the existing wet pit and lift station were used to divert the flow into the Port Arthur Sewerage System. Flow from the station is by gravity to the Third Avenue Lift Station, thence to the Pioneer Park Lift Station. Flow then continues by gravity until it joins the interceptor between the Lake Charles Lift Station and the Mainline Pump Station. The map of this system is shown in Figure 23.

The primary problems of this system have been the odors at the Third Avenue Lift Station, corrosion of the downstream gravity line, and odor and corrosion downstream of the Pioneer Park Lift Station. Venting with a high stack at the Third Avenue Lift Station removed the odor from the houses adjacent to the station only to have the houses one block downwind experience the odor. Attempts were made to mask the odor with equally disappointing results. A major shortcoming of masking by substituting a new odor is that it fails to abate corrosion of the concrete structure and pipe. The most recent failure of pipe due to corrosion occurred immediately downstream of the Pioneer Park Lift Station in 1971. The failure required the replacement of 150 feet of 30 inch diameter pipe.

Sulfide Levels

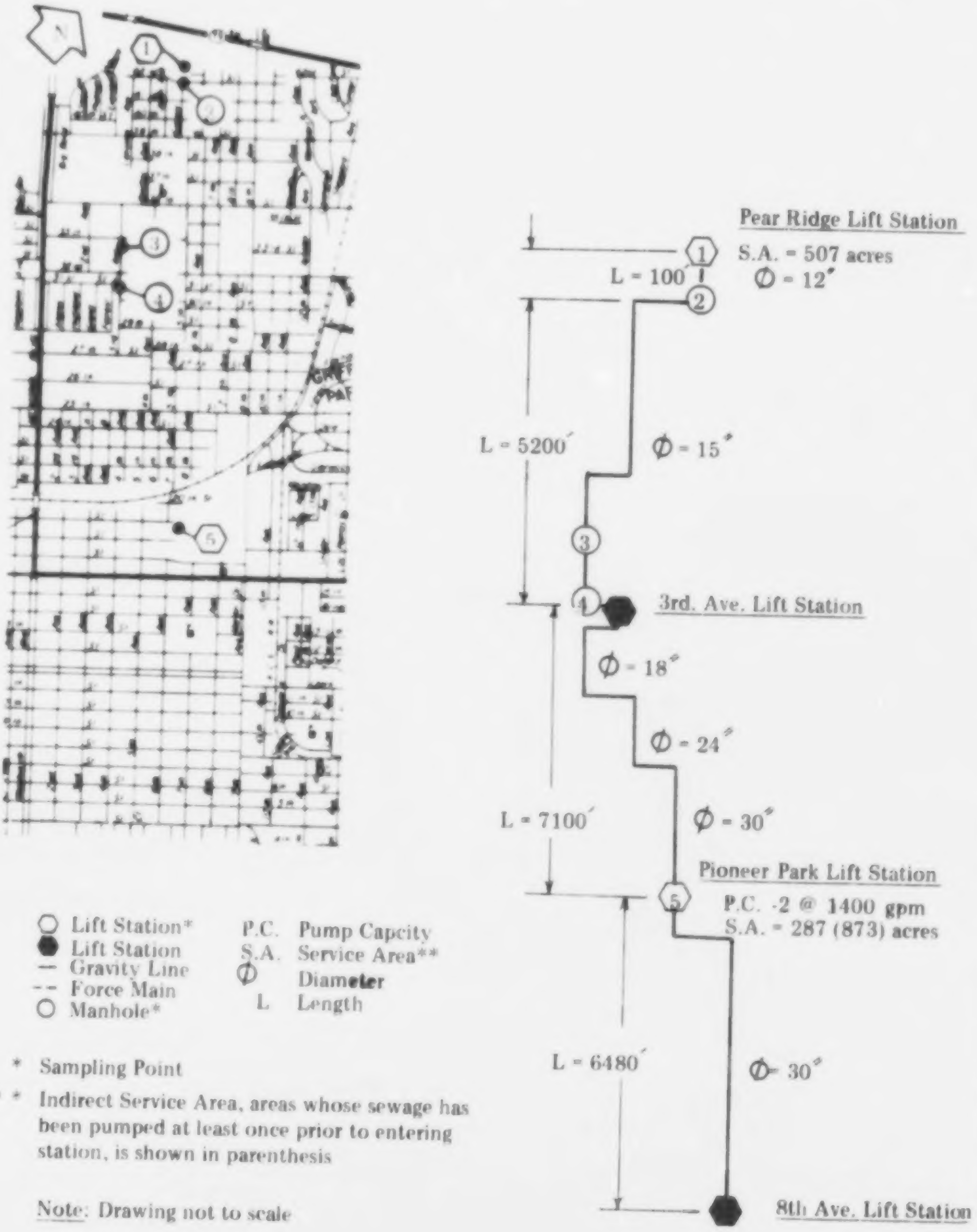
The evaluation of sulfide levels in this system, prior to the installation of control equipment, was conducted for only a brief period during the summer of 1969. High infiltration during most of the period influenced the data obtained and sulfide levels found were not compatible with sulfide problems evidenced downstream of the station. The principle problem was the generation of sulfides in the Pear Ridge collection system and subdequent release at the lift station and in the downstream gravity line. Sulfide levels found in the wet wells of the Pear Ridge and Pioneer Park Lift Stations will be found in the data presented in the Design and Operation section to follow.

SYSTEM DESIGN AND OPERATION

Two sites were selected in this system for the installation of sulfide control equipment. These installations, Pear Ridge Lift Station and Pioneer Park Lift Station, were included in Phase II of the project. These two stations were serving to create turbulence thereby releasing hydrogen sulfide and not serving as sulfide generators as in the case of force mains. This condition defined the basic design concept for control equipment, the oxidation of existing sulfides and providing a dissolved oxygen residual in the sewage to retard sulfide buildups downstream.

Pear Ridge Lift Station

The site of the former sewage treatment plant had adequate space available and thereby did not impose any size or location restrictions for equipment that would be installed outside the station; however space inside the station was limited. The length of the force main being only 100 feet imposed restrictions on choice of equipment. The experience at the Nineteenth Street-Stillwell Boulevard Lift Station ruled out the injection of gaseous oxygen or air into the force main. The use of U-Tubes was also


N
1
2
3
4
5
Pear Ridge Lift Station
S.A. = 507 acres
Ø = 12"
L = 100'
L = 5200'
Ø = 15"
3rd. Ave. Lift Station
Ø = 18"
Ø = 24"
L = 7100'
Ø = 30"
Pioneer Park Lift Station
P.C. -2 @ 1400 gpm
S.A. = 287 (873) acres
L = 6480'
Ø = 30"
8th Ave. Lift Station
○ Lift Station*
● Lift Station
— Gravity Line
-- Force Main
○ Manhole*
P.C. Pump Capcity
S.A. Service Area**
Ø Diameter
L Length

* Sampling Point

** Indirect Service Area, areas whose sewage has been pumped at least once prior to entering station, is shown in parenthesis

Note: Drawing not to scale

Figure 23. Pear Ridge System

eliminated due to the configuration of the station. Considering all these factors, a decision was made to install a second pressure tank. Details of the station and pressure tank installation are shown in Figure 4. Following the installation of the pressure tank, a concentrated sampling program was conducted from June 16, 1970 until July 28, 1970 to evaluate the equipment performance. The data collected during this period are shown in Table 16. The four sampling points are identified in Figure 23.

The total sulfide concentration coming into this station for the test period averaged 3.88 mg/l. The effect of recirculation on the reduction of sulfides was demonstrated; however, the reduction was not of the same magnitude as previously observed for the other pressure tank locations. The pressure tank effluent was clearly at an acceptable sulfide concentration. The dissolved oxygen content of the sewage leaving the tank was approximately 66 percent of saturation. Sulfide in the discharge of the force main was found to increase slightly while the dissolved oxygen level was decreased by about one mg/l. During the test period and operation of this equipment through 1971, odor complaints downstream were eliminated. On one or two occasions, odor complaints were reported and these were associated with periods at which the pressure tank was not operating.

The noise generated by the blower and air release valve at the top of the tank, although not anticipated to be a problem, proved troublesome. Mufflers were added and a wall was erected between the equipment and the nearest houses. The noise was then at an acceptable level.

Pioneer Park Lift Station

The second phase of the study included the Pioneer Park Lift Station in the sulfide control program. The recent development of the U-Tube aeration concept offered a potential method for control. Installation requirements, which included space in the dry pit and pump characteristics, were evaluated and it was found that U-Tubes could be installed. The use of compressed air in lieu of a venturi aspirator was selected. This was the first prototype installation in the United States using a U-Tube with compressed air in a sewer system.

The station consisted of two 1400 gpm pumps that alternate at low flows. Both pumps operate during peak flow periods. The station operation therefore required the installation of two U-Tubes. The U-Tube configuration after the installation is shown in Figure 24.

Air to the two U-Tubes was supplied by a single blower located outside the station with piping and controls arranged to alternate distribution to each tube. Injection was accomplished by drilling holes around the periphery of the expanded section and welding a distribution collar over the holes. Air was regulated by using a valve and rotameter. The blower was set to come on ten seconds after the pump started and stopped with the pump cycle. Continuous operation of the blower was not considered desirable for fear of air-locking the system.

Table 16

SEWAGE CHARACTERISTICS

Pressure Tank Test Program
Pear Ridge Lift Station - Force Main
[Test Period June 16 - July 28, 1970]

Sampling Point	Temp. (°C)	pH	Total Sulfides (mg/l)	Dissolved Sulfides (mg/l)	Dissolved Oxygen (mg/l)	BOD (mg/l) Unfiltered	BOD (mg/l) Filtered	COD (mg/l)
Pear Ridge Lift Station Wet Well	Ave. 28.5	6.8	3.9	3.1	0	253	185	531
	Max. 30.0	7.4	6.3	6.0	0	360	250	681
	Min. 27.0	6.6	1.8	1.0	0	192	120	413
Pressu[illegible]nk Influent	29.1	6.8	1.1	0.89	0.1	241	180	505
	30.5	7.3	2.7	2.2	1.2	350	310	631
	27.0	6.6	0.1	0	0	170	24	372
Pressure Tank Effluent	29.5	6.9	0.1	0	4.9	269	210	519
	31.0	7.2	0.2	0	7.0	390	380	707
	28.0	6.6	0	0	4.0	162	126	353
42nd & Eunice (Force Main Discharge)	28.7	6.6	0.2	.05	3.9	225	166	500
	30.0	7.4	3.0	1.5	5.0	310	240	736
	27.0	6.7	0	0	0	130	90	328

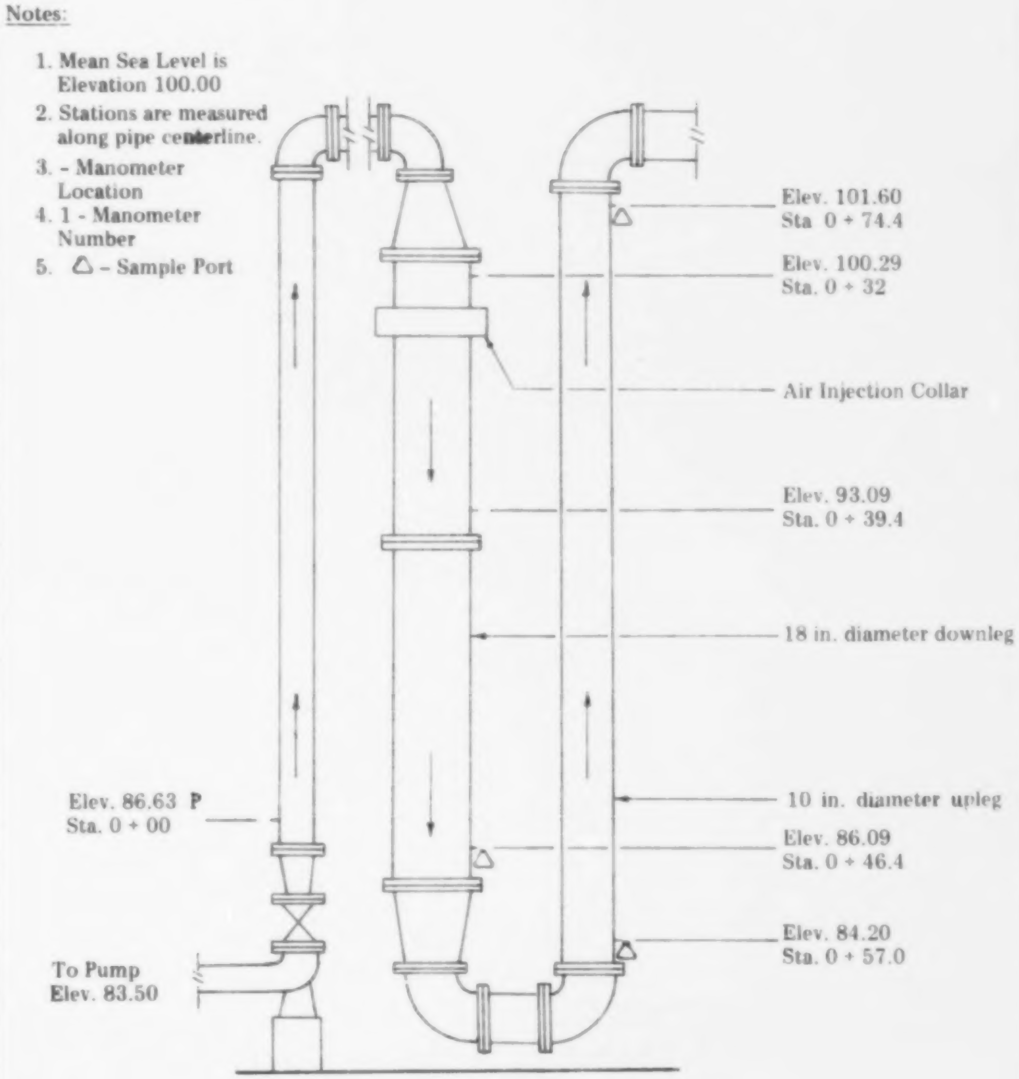

Notes:
1. Mean Sea Level is Elevation 100.00
2. Stations are measured along pipe centerline.
3. - Manometer Location
4. 1 - Manometer Number
5. △ - Sample Port
Elev. 101.60
Sta 0 + 74.4
Elev. 100.29
Sta. 0 + 32
Air Injection Collar
Elev. 93.09
Sta. 0 + 39.4
18 in. diameter downleg
10 in. diameter upleg
Elev. 86.63 P
Sta. 0 + 00
Elev. 86.09
Sta. 0 + 46.4
Elev. 84.20
Sta. 0 + 57.0
To Pump
Elev. 83.50

Figure 24. U-Tube Configuration at Pioneer Park Lift Station

U-Tube system design was based on pilot data developed by Rocketdyne for a 2-inch diameter prototype installation (51) and on data from a full-scale installation at Jefferson Parish, Louisiana (52). Downleg velocity should be in the range from 1.5 to 2 ft/sec to maximize bubble contact time. Velocity in the return bend and upleg should be in the range from 4 to 6 ft/sec to prevent solids deposition. The basis of design was as follows:

Flow Rate	1400 gpm
Air Injection Rate	40 cfm
Air/Water Ratio (Volume)	21 %
Downleg	
Pipe Diameter	18 inches
Velocity	1.8 fps
Upleg	
Pipe Diameter	10 inches
Velocity	5.7 fps
Downleg Length - injection collar to return bend	14 feet

The evaluation of the U-Tube was to incorporate hydraulic characteristics, sulfide control and oxygen transfer characteristics. To enable proper evaluation, sampling ports were placed at the pump and discharge point with provisions for connecting manometers at six points. The manometer locations are shown in Figure 24.

The evaluation of the U-Tube hydraulic characteristics required measurement of both liquid and air flow rates. The liquid flow was controlled by a gate valve located immediately downstream of the pump and measured downstream in the gravity sewer by velocity-area measurements. Velocities were measured by means of a pygmy current meter in the first manhole downstream in the gravity sewer. When three successive measurements were obtained for a fixed time in which the revolutions did not vary by more than one percent, the flow was taken as the mean of the three velocity-area measurements recorded. The only problem encountered with this method of measurement was the frequent cleaning of the current meter due to debris such as hair interfering with the cup rotation.

The most important hydraulic characteristic pertinent to U-Tube operation is system pressure losses. For the purpose of the study, system losses were measured from the gate valve to the discharge (as shown in Figure 24). The original configuration of the lift station was not evaluated hydraulically prior to the installation of the U-Tube and comparisons of system losses under actual conditions was not possible. Calculation of system losses for the original system would indicate that these would be minor, i.e. less than one psi or 2.3 feet for all conditions of flow. This represents the friction and minor losses designed into the station.

The losses through the U-Tube configuration were first evaluated without air injection. Head loss at design flow and no air was 715 feet of water or 3.25 psi.

The compressor could actually only inject a maximum of 15 cfm for air:water ratio of 8.1 percent. Operations at maximum air flow or air:water ratio resulted in an average system loss of 6.6 feet of water or 2.86 psi. It was possible to vary the air:water ratio from 3.4 to 8.1 percent at the design liquid flow, but system head losses measured in this range were inconclusive.

The ability to inject a greater amount of air to alter the air:water ratio would have permitted optimization of this device using compressed air. In addition to finding an optimum air:water ratio, it would have permitted a more valid comparison with other installations. Air flows of 43 cfm have been obtained at installations using aspiration devices with U-Tubes. This is three times the air flow obtained with the U-Tube in this study due to equipment limitations.

The second aspect of the U-Tube operation was that of oxygen transfer characteristics and its ability to function as a sulfide control device. Prior to any detailed testing, the system was operated for a period of approximately one month. During this period sewage temperatures were low and the sulfide levels found were not representative of the system when sewage temperatures are higher. Data obtained during this period are shown in Table 17.

Sewage passing through the U-Tube was characterized by minor reductions in both total and dissolved sulfides. The dissolved oxygen residuals found in the discharge were found to increase significantly. These tests were performed at a constant air:water ratio of 8 percent which represented an oxygen equivalent of 19 mg/1.

The injection of air or oxygen into sewage during this study had as a primary objective the control of hydrogen sulfide and not the evaluation of total oxygen transferred. It was felt desirable to evaluate the oxygen transfer characteristics of the U-Tube using compressed air to permit comparisons with other studies. A period of intense testing on the U-Tube provided the opportunity for an expansion of the standard testing to include additional oxygen evaluations.

Sewage void of oxygen usually has a deficit that must be satisfied before a dissolved oxygen residual can be obtained. The test most frequently used to describe this is the Immediate Dissolved Oxygen Demand (IDOD). The test yields the amount of oxygen consumed in fifteen minutes. The ability to obtain a dissolved oxygen residual upon aerating sewage would imply the immediate oxygen demand was satisfied and the total oxygen transferred would be represented by the sum of the IDOD and the residual.

The initial procedure for the extended testing of the U-Tube called for the standard IDOD test to be run only on the U-Tube influent. Tests were performed on this basis for a short time and then the IDOD was added to the effluent analysis. The next modification was to determine the oxygen demand for a 30 second incubation period on both the influent and effluent of the U-Tube. This was to provide data that would be more representive

Table 17

U-Tube Operation - Constant Air:Water Ratio (8.1)

Pioneer Park Lift Station
[Test Period Oct. 30 - Nov. 28, 1970]

			PARAMETER				
Sampling Point	Temp. (°C)	pH	Total Sulfides (mg/l)	Dissolved Sulfides (mg/l)	DO (mg/l)	BOD (mg/l)	COD (mg/l)
Wet Well	Ave. 24.9	7.0	1.1	1.0	0.2	187	471
	Max. 26.0	7.1	4.3	4.3	5.0	265	636
	Min. 21.0	6.6	0.1	0.0	0.0	130	242
Station Discharge	23.7	7.0	0.9	0.7	2.7	198	461
	25.0	7.1	5.0	4.0	9.0	390	700
	21.0	6.8	0.0	0.0	0.0	50	180

of the contact time in the U-Tube which was 17 seconds at design conditions.

The period of extended testing was during July when sewage temperatures are near the maximum and when sulfide levels are highest. The data collected for this period are shown in Table 18. Sulfide levels were reduced by only a small amount and the residuals were in excess of desirable limits. Dissolved oxygen residuals were lower than anticipated; however, when considering reductions in the IDOD, the total oxygen transferred varied from 1 to 40 percent. The 15 minute and 30 second oxygen demand tests are plotted in Figure 25.

There were several conditions observed during the testing of this system that should be noted. First, as long as the blower was operating, odors were not observed at the station. There was a high degree of turbulence at the discharge point resulting in a foam collecting on the surface of the gravity flow. This foam was usually gone or only trace amounts observed at a point approximately 400 feet downstream of the station. Although not routinely checked, the sulfide level at this location was generally found to be at an acceptable level. This would indicate that the sulfides were either released or oxidized in the gravity line. The absence of odor would indicate that the latter was probably the case. Prior to the installation of the U-Tube, odors were severe downstream from the station.

MAINLINE SYSTEM

The Mainline System as defined for purposes of the study consists of the two largest sewage transfer stations in the city. The two stations are the Lake Charles Lift Station and the Mainline (Lakeview) Pump Station. Both stations are located on the Lakeshore Interceptor with the Mainline Station making the final transfer of sewage from the collection system to the sewage treatment plant. The two stations were included in Phase II of the project. Details of this system are shown in Figure 26.

Lake Charles Lift Station

The Lake Charles Lift Station is the second largest sewage lift station in the Port Arthur Sewerage System and handles the flow from the Lakeshore and Stillwell Systems. The major problem at this location is the sulfides arriving at the station and their subsequent release and not generation. Sulfide levels were studied indirectly at the station as a part of other systems and not in terms of the station serving as a sulfide generator. There was sufficient evidence that excessive amounts of hydrogen sulfide gas were being released as it had a history of odor problems and deterioration of concrete in the wet wells and in the downstream sewer. Sulfides were released in the wet well and at the discharge point of the lift pumps.

System Design and Operation

The criterion for sulfide control at this location was the oxidation of sulfides and development of a dissolved oxygen residual. The methods previously employed for sulfide control at lift stations, i.e. pressure tanks and air-injection into U-Tubes, had several limitations at this site. Aesthetic considerations related to land use and equipment noise

Table 18

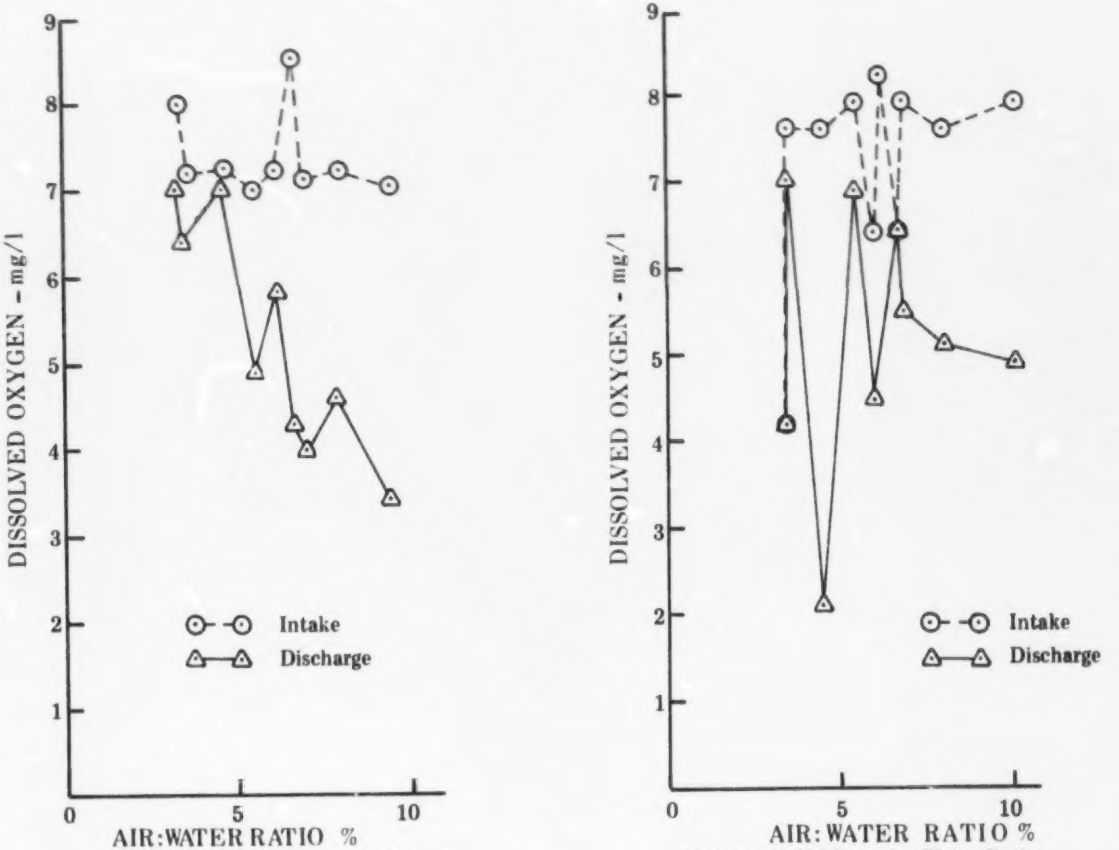
U-Tube Operation - Variable Air:Water Ratios

Pioneer Park Lift Station [Test Period July, 1971]

Sampling Point	Pump discharge gpm	Air:Water Ratio %	Oxygen Applied (mg/l)	Temp. (°C)	pH	Total Sulfides	Dissolved Sulfides	DO (mg/l)	15 min. IDOD (mg/l)	30 sec. IDOD (mg/l)	Head Loss Across System (ft)
I *	1317	3.4	8.2	30	6.9	4.3	4.0	0	10.2	7.6	6.4
D * *						2.6	2.4	0	9.4	7.0	
I	1319	4.5	10.9	30	6.9	5.3	4.2	0	10.2	7.6	6.5
D						2.7	2.3	0	10.1	7.1	
I	1325	4.5	10.9	30.7	7.1	1.7	1.6	0	6.3	-	6.5
D						0.9	0.6	1.6	3.5	-	
I	1300	5.7	13.8	33.7	7.2	2.3	2.1	0	7.9	-	6.6
D						1.5	1.1	1.1	6.2	-	
I	1314	6.3	15.3	30	6.9	5.0	4.8	0	10.2	8.2	6.6
D						2.8	2.3	0	8.8	8.1	
I	1264	7.1	17.2	32	7.2	1.8	1.5	0	10.6	-	-
D						1.5	1.1	1.5	6.4	-	
I	1300	8.1	19.6	29	6.9	4.2	3.8	0	10.2	7.6	7.1
D						3.8	3.0	0	7.6	7.1	
I	1274	8.2	19.8	29.6	7.2	2.4	2.0	0	9.5	-	-
D						1.7	1.2	1.2	6.8	-	

* Pump Discharge

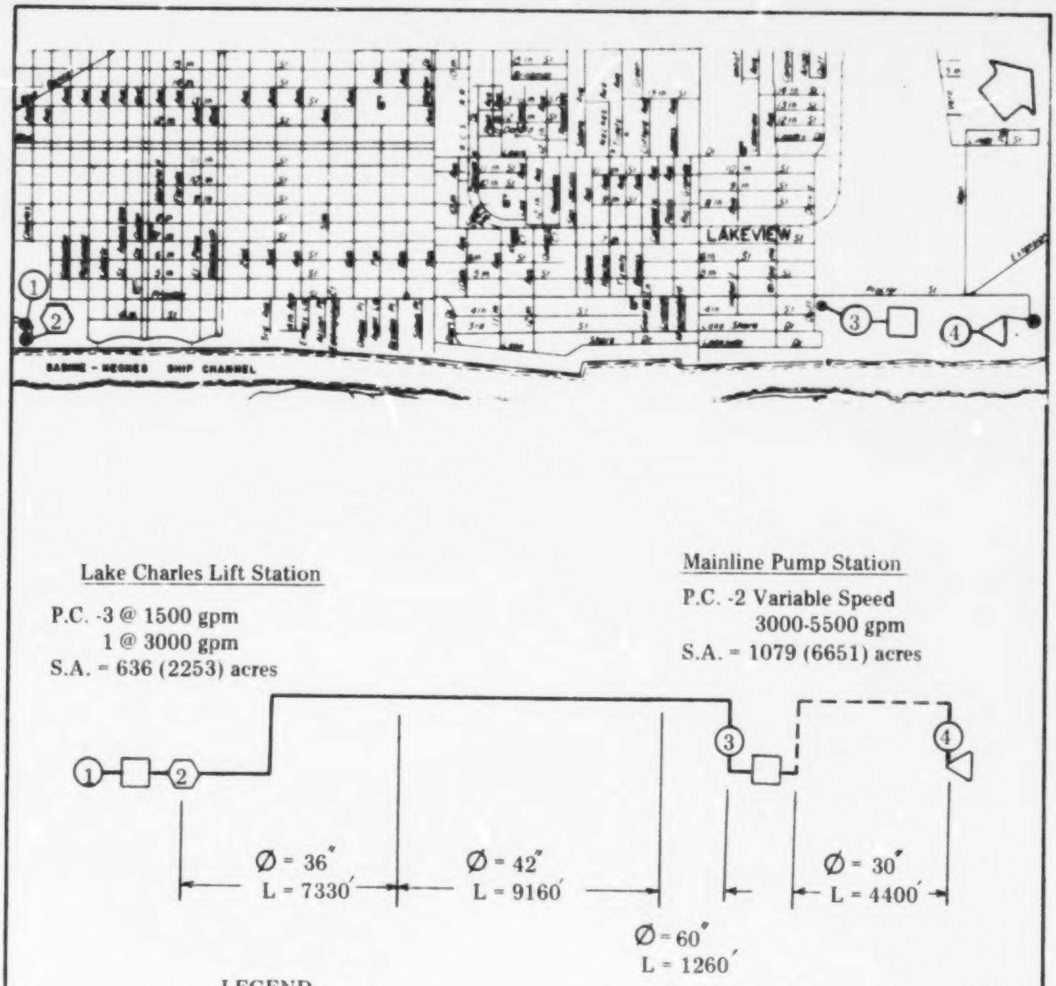
* * U-Tube Discharge



15 Minute Oxygen Demand vs. Air:Water Ratio - Pioneer Park Lift Station

30 Second IDOD vs. Air:Water Ratio
Pioneer Park Lift Station

Figure 25


SABINE - NECHES SHIP CHANNEL
LAKEVIEW
1
2
3
4
Lake Charles Lift Station
P.C. -3 @ 1500 gpm
1 @ 3000 gpm
S.A. = 636 (2253) acres
Mainline Pump Station
P.C. -2 Variable Speed
3000-5500 gpm
S.A. = 1079 (6651) acres
Ø = 36"
L = 7330'
Ø = 42"
L = 9160'
Ø = 60"
L = 1260'
Ø = 30"
L = 4400'

LEGEND

○	Manhole	P.C.	Pump Station
⬡	Lift Station	S.A.	Service Area
□	Pump Station	Ø	Diameter
—	Gravity Line	L	Length
- - -	Force Main		
◁	Main Port Arthur Wastewater Treatment Plant		

Figure 26. The Mainline System

eliminated the two previous methods employed. Further, the station configuration and available pump heads would not permit consideration of the other control methods.

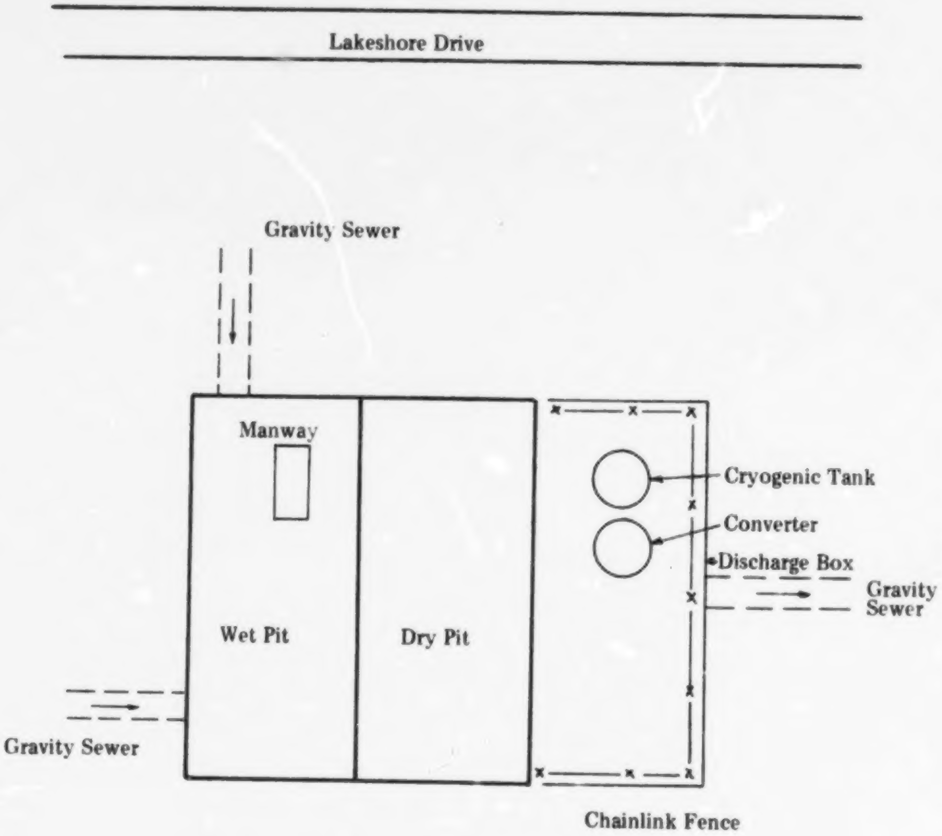
The station has four lift pumps that discharge into a common discharge box located outside the station with each pump having a separate discharge pipe. Two of the pumps alternate during low and normal flows with the extra pumps operating only during periods of excessive infiltration. As the most severe sulfide problems were associated with low flows, it was felt that the installation of U-Tubes on the low lead pumps would provide the sulfide control desired. The design called for use of gaseous oxygen in lieu of an aspiration device or compressed air. Details of the Lake Charles Lift Station are shown in Figure 27. The U-Tubes were essentially the same as shown in Figure 24 for the Pioneer Park Station. The major exception was the depth of tubes, diameter, and method of oxygen injection.

The choice of U-Tube aerators presented a problem due to pump characteristics. The available depth and space was adequate for U-Tube installation; however, the pump head was inadequate to handle the anticipated head losses of a diffused air U-Tube. The liquid level in the wet well could have been raised to obtain better hydraulic characteristics, but was not considered desirable. Increasing the operation level in the wet well would result in flooding of the gravity lines and increasing the detention time. These factors led to the choice of injecting gaseous oxygen in the U-Tube. This was the first installation of a U-Tube aeration device employing gaseous oxygen. The basis of design was as follows:

Flow Rate	750 gpm
Oxygen Injection Rate	0.4 cfm
	0 to 48 mg/l
Downleg	
Pipe Diameter	14 inches
Velocity	1.6 fps
Upleg	
Pipe Diameter	10 inches
Velocity	3.1 fps
Downleg Length - injection collar to return bend	15.3 feet

The pump capacity of 750 gpm was used for design; however, it was later learned that the actual pump capacities were 1100 to 1500 gpm. This error resulted in a less than optimum design and oxygen transfer efficiency. The system was designed to achieve 80 to 90 percent oxygen transfer based on projections made from air injection studies on a pilot system by Rocketdyne (51). Oxygen transfer efficiencies attained were lower because of the reduction of 50 percent in bubble contact time as will be discussed later.

The oxygen was initially injected through a straight tap at one location at the beginning of the expanded section of the U-Tube. This was later changed to four straight tap injection points. Problems were still


Lakeshore Drive
Gravity Sewer
Manway
Cryogenic Tank
Converter
Discharge Box
Gravity Sewer
Wet Pit
Dry Pit
Gravity Sewer
Chainlink Fence

Note: Oxygen injection into U-Tubes located in the Dry Pit.
U-Tube configuration similar to Figure 7 and Figure 24.

Figure 27. Lake Charles Lift Station

experienced in achieving oxygen transfer and it was felt that the oxygen was short circuiting. Finally, copper tubes with a series of holes along the length with a plugged end were inserted at each injection point. The tubes were given a radius that pointed downstream to prevent rag build-up on the diffusers.

During the period of study it was discovered that the major problem was not with the methods of injection but with the methods of sampling. Samples were obtained by opening the sampling ports and after a short period, collecting the sample. This method failed to yield any dissolved oxygen, regardless of the oxygen feed rate. Later, it was found that by permitting the sample ports to remain open with a continuous flow a dissolved oxygen residual was found in the samples.

There were several problems encountered with this installation that prevented a long range sampling program to be effectuated. In addition to the sampling problem, operational problems were encountered. Oxygen appeared to be collecting in the upper section of the U-Tube which restricted the flow. The effect was to completely block the flow when the wet well was low. This condition resulted from the minimal operational head of the pumps due to excessive impeller wear. The pumps were rebuilt prior to additional testing.

A concentrated period of sampling was conducted during July and August, 1971 on this installation. This sampling was restricted to the sewage characteristics of sulfides and dissolved oxygen transfer. Head losses due to oxygen injection were considered to be minimal with the major losses resulting from the U-Tube piping design. Sewage flow rates were taken at the rated capacity of the pumps for purposes of calculating applied oxygen rates. It was felt that errors introduced by this assumption for purposes of calculating the oxygen:water ratios would not be significant. The station configuration prevented any reasonable measurement or estimation of flow without major renovations or aquisition of special flow measuring equipment. These items were not originally scheduled for the project and therefore not provided for in the evaluation phase.

Data obtained from the period of intense study are given in Table 19. Four oxygen feed rates were applied starting at 6.27 milligrams-per-liter and increased in equal intervals to 25.1 milligrams-per-liter. The complete oxidation of sulfides was not accomplished at any oxygen feed; however, the amount oxidized increased with increased oxygen. Reduction to acceptable levels was never achieved because of the error in pumping capacities.

The oxygen transfer of the system increased with increased oxygen feed. This held for the reduction in the IDOD and also for the magnitude of dissolved oxygen in the U-Tube discharge. The increased reduction plus the increased level of dissolved oxygen are misleading when considered with the amount of oxygen applied. At the oxygen feed of 6.3 milligrams per liter, sixty two percent of the oxygen was transfered. The percentage of oxygen transfered decreased with increased oxygen feed reaching a minimum of 38 percent for the ranges tested.

Table 19

SEWAGE CHARACTERISTICS

U-Tube Operation with Oxygen Injection
Lake Charles Lift Station
[Test Period: July - August, 1971]

Sampling Point	Oxygen Applied (mg/l)	Temp. (°C)	pH	Total Sulfides (mg/l)	Dissolved Sulfides (mg/l)	DO (mg/l)	IDOD (mg/l)
I*	6.3	28.3	7.1	2.8	2.5	0	4.6
E		28.3	7.1	2.1	1.8	1.7	2.4
I	12.5	28.1	7.1	3.2	2.9	0	4.5
E		28.1	7.1	2.3	2.1	3.6	2.1
I	18.8	28.3	7.1	3.2	2.9	0	5.1
E		28.3	7.1	2.1	1.8	4.4	1.9
I	25.1	28.3	7.1	3.5	3.2	0	5.4
E		28.3	7.1	2.2	1.8	5.5	1.3

PARAMETER spans Temp. through IDOD.

*** I - U-Tube Influent, E - U-Tube Effluent**

Because of the error in pump capacity, the average detention time at this installation was 17 seconds as compared with 30 seconds at the Pioneer Park Station. With a 2-fold increase in detention time, it can be reasonably projected that oxygen transfer efficiency would have been nearly 100 percent at the lower injection rates and approximately 70 percent at the higher rates tested.

Mainline (Lakeview) Pump Station

This pump station receives the combined flows of all the systems described in the study. The station was erected in 1961 under the same bond program that built the sewage treatment plant. The station contains two variable speed pumps that operate to provide a minimum flow of 3000 gpm to the plant. A 30-inch diameter force main connects the pump station with the sewage treatment plant. This line is 4,400 feet in length.

The force main discharges into an open channel at the sewage treatment plant. The sewage then passes through Barminutors thence to a Parshall flume and Detriters. Corrosion of this equipment has been a continuing process and protective coatings have failed to check the corrosive attack attributable to hydrogen sulfide. The odor around these inlet facilities was of such intensity that the entire sewage treatment plant was considered to be operating improperly.

Only a limited amount of data was obtained for sulfide conditions at the wet well and force main discharge prior to installation of sulfide control. The data obtained from the wet well and at the force main discharge are shown in Table 20. As indicated in the table, the sampling occurred during the months when the sewage temperature was low with an average value of twenty-one degrees Centigrade. The presence of total and dissolved sulfides in significant quantities during this period serves to emphasize the sulfide problem experienced in this sewerage system. The force main served as a sulfide generator at this location by increasing both total and dissolved sulfides by an average amount that exceeded two mg/l.

The need to install sulfide control measures at this location was apparent when considering the corrosion and odor problems at the plant. The existence of only one pipe to the treatment plant from the station and its handling of all the city's sewage imposed special considerations for installation and operation of sulfide control facilities. A pressure release valve located outside the pump station provided access to the force main without interrupting operations. There were doubts expressed as to the effectiveness of injecting air at the top of the pipe and without the use of diffusers as called for in the original design of the other installations. The blower and necessary piping were installed and equipment placed in operation November 21, 1971.

The first blower installed was set to deliver fifty cfm and was operated at this rate while tests were performed to evaluate the effects of

Table 20

Sulfide Levels
Mainline (Lakeview) Pump Station

NO AIR INJECTION

Date	Sampling Point	Temp. (°C)	pH	Total Sulfides (mg/l)	Dissolved Sulfides (mg/l)	DO (mg/l)
				PARAMETER		
Nov. 12-18, 1971	WW *	22.6	7.0	2.5	2.4	0
	D	22.7	7.0	5.1	5.0	0
Nov. 25, 1971	WW	22.0	7.0	3.3	3.1	0
	D	22.0	7.0	6.1	6.0	0

AIR INJECTION

Date	Sampling Point	Temp. (C°)	pH	Total Sulfides (mg/l)	Dissolved Sulfides (mg/l)	DO (mg/l)
				PARAMETER		
November 21, 1970	WW *	22.4	7.0	0.8	1.0	0
	D	22.2	7.0	1.4	1.3	0
December 19, 1970	WW	22.0	7.0	2.6	2.2	0
	D	22.0	7.0	2.3	2.2	0
July 13-16, 1971	WW	–	–	–	–	–
	D	28.9	7.1	0.5	0.4	0

* WW - Wet Well; D - Force Main Discharge

aeration. The sewage temperature during this period was approximately 22^{o} Centigrade. Data collected during this period are shown in Table 20. The incoming sulfides during this period were low and although the temperature of the sewage was low, the air injection failed to prevent additional sulfides from being generated. The blower was replaced by one capable of delivering 110 cfm. This increased the air feed from 1.7 to 3.67 cubic-feet-per-minute per inch diameter and increased the applied oxygen from 27.3 to 66.7 milligrams-per-liter based on the minimum pumping rate for the station. The temperature of the sewage during this period was approximately 29^{o} Centigrade indicating a high sulfide generating potential in the force main. Data collected during July, 1971 shown in Table 20 indicate control of the sulfides at the increased air feed. After installation of the larger blower, sulfide odor problems at the sewage treatment plant were eliminated.

SECTION VII

EVALUATION OF OXYGEN SOURCES AND METHODS OF INJECTION

The study proposed to evaluate the effectiveness of controlling hydrogen sulfide through the use of oxygen. Two sources of oxygen were utilized, pure oxygen and air, and three basic methods were used for entrainment. Minor modifications were made to the original designs when conditions dictated the need to meet an individual station requirement or configuration. There were a total of eight control sites used during the course of the study with two sites using both air and pure oxygen. One site utilized both sources of oxygen for injection into a force main providing a unique opportunity for comparison and evaluation.

The use of oxygen, regardless of its source, can effectively control sulfides in sanitary sewage by one of two mechanisms. The first is the oxidation of existing sulfides to acceptable limits and second, is the inhibition of sulfide generation. There were several methods used for the entrainment of air or oxygen gas into the sewage which proved to be effective. Each method had its own distinct or unique features which should be utilized in design. The critique of the operation experience will be discussed as follows: methods of injection; oxygen; air; pressure tank; and U-Tube. Consideration will be given to effectiveness, operational problems, maintenance, site requirements and other special features where applicable.

Methods of Gas Injection in Force Mains

The original design for air and oxygen injection called for the installation of rather elaborate diffusion facilities as shown in Figures 4 and 5. It was anticipated that diffusers installed in force mains would collect rags and other debris thereby impeding flow and creating additional maintenance problems. This problem did not materialize during the period of study; however the potential for flow restriction must be recognized. At two sites the expanded diffuser section was installed in the force main where either air or oxygen achieved sulfide control. One site used air injection through a straight tap at the pipe crown which proved equally effective in sulfide control. Considering these two methods of air injection into force mains, there does not appear to be any significant difference when considering only sulfide control, as both were effective.

A second consideration of air or oxygen injection is the amount of oxygen transfered and the maintenance of a residual dissolved oxygen at the force main discharge. Oxygen transfer was not the primary objective of the study; however, the data obtained throughout the study would appear to favor the diffuser tubes over straight taps.

The diffuser installation required 2.25 cfm per inch diameter to control sulfides and obtain a dissolved oxygen residual. This represented a volumetric air to water ratio in the range of 17 to 38 percent. The diffusers were applying oxygen on a weight basis of 60.4 mg/l. These compare with the straight tap where air was applied at 3.66 cfm per inch diameter with sulfide control achieved, but without obtaining a dissolved oxygen residual. The volumetric air to water ratio at this site was 27 percent. This represented an application of oxygen on a weight basis in the range of 16 to 36 mg/l.

The preceeding discussion clearly indicates the importance of parameter selection when evaluating air or oxygen injection for sulfide control. In the instance cited, selection of air feed on the basis of pipe diameter would indicate the diffuser as being the most effective method of air or oxygen entrainment. The major limitation to this form of expression is the failure to relate the gas feed rate to fluid flow. Expressing the air or oxygen feed on a weight basis clearly indicated that injection through a straight tap as the most effective for sulfide control and that the additional cost of diffusers is not warrented.

PURE OXYGEN INJECTION

Gaseous oxygen was used at a total of five locations in the city. Three of the sewage pump stations had force mains of significant length while a forth transfer station had a very short force main and should be classified as a lift station. The fifth location was a lift station where oxygen was injected into a U-Tube. Discussion of the U-Tube as a sulfide control device using gaseous oxygen will be deferred to a later section. Details of these stations are given below which indicates their physical variations.

Station	Force Main Diameter Inches	Length Feet	Pump Capacity gal/min	Detention Time (normal flow) Minutes
Grannis	8	3150	600	13.8
Railroad Ave.-Thomas Blvd.	16	3850	1200	33.4
19th Street-Stillwell Blvd. (Alligator Bayou)	16	600	2350	2.6
Smith-Young (39th Street)	8	5427	350	41.3
Lake Charles Lift Station	8	U-Tube	1500	1.0

The configuration of the junction box prevented a complete evaluation of the Grannis Station operation; however, the data obtained indicated that sulfide control was being accomplished. Operation of the 19th Street

Lift Station demonstrated that the injection of gaseous oxygen into short force mains is ineffective at low oxygen feed rates, and at higher oxygen feed rates the oxygen is wasted to the atmosphere. The latter results from the creation of a two phase flow regime. This short force main was equipped with diffusion facilities as shown in Figures 4 and 5. The ability to diffuse the oxygen by small bubbles was without benefit for the system configuration and operation.

Injection of oxygen at the Smith-Young Pump Station never achieved the desired level of performance for either sulfide control or oxygen transfer. Failure to achieve sulfide control is attributable to the physical configuration of the force main. The radical change in the force main profile where it was depressed to pass under a drainage ditch resulted in a blockage that trapped oxygen in the upstream pipe. The importance of the force main profile becomes manifest when oxygen or air is planned for sulfide control. The severity of the problem would have been intensified if air had been used in lieu of oxygen.

It was possible to inject oxygen at one cfm without adversely affecting pumping characteristics and at this rate sulfides were reduced but not completely controlled. This rate represented a volumetric oxygen to sewage ratio of 2.14 percent or an applied oxygen of 24.6 mg/l. It is significant to note that sulfides were controlled at the midpoint of the force main.

The most comprehensive data for oxygen injection were obtained at the Railroad-Thomas Boulevard Pump Station. At this location an optimum feed rate for both sulfide control and dissolved oxygen residual was obtained. The optimum feed rate was 2 cfm and represented a volumetric oxygen to sewage ratio of 1.25 percent. This represented an oxygen application of 14.4 mg/l. The data indicated an average oxygen residual at the force main discharge of 0.4 ppm which would indicate that 14 mg/l of oxygen was either consumed in the oxidation of sulfides, used in meeting the oxygen demand, wasted to the atmosphere, or utilized by a combination of these mechanisms.

The Smith-Young and Railroad-Thomas Boulevard Pump Stations have very similar velocities and detention times although their diameters and flow rates are different. The sewage strength as measured by BOD was not significantly different during the respective test periods and the other sewage characteriestics were similar. The ability to control sulfides using oxygen was demonstrated in each instance although the amount of oxygen required was different as well as the degree of control. The conditions observed clearly indicate that additional parameters are involved in the overall problem of sulfide generation and control.

Air Injection

Atmospheric oxygen was used at a total of five locations in the city. The applications were force main injection, pressure tanks and U-Tubes.

The injection of atmospheric oxygen into force mains will be discussed here and its use in the other applications will be deferred to a later section. Atmospheric oxygen, when injected into force mains, can be effective in the oxidation of existing sulfides and prevention of additional sulfides from being generated.

The stations where atmospheric oxygen was injected into force mains are given below with information pertinent to the study.

Station	Pump Capacity gpm	Force Main Diameter Inches	Length	Detention Time (minutes)
Railroad Ave.- Thomas Blvd.	1200	16	3850	33.4
Mainline (Lakeview)	3000*	30	4040	53.9

* design minimum flow conditions

Certain physical aspects of these two stations are similar, such as force main length and detention times, while others, such as force main diameter and pumping capacity are widely divergent. The sewage characteristics at the two locations were also similar.

The air requirement to control sulfides at the Railroad Pump Station was equivalent to 2.5 cfm per inch diameter while at the Mainline Station it was 3.7 cfm per inch diameter. This corresponded to a volumetric air: water ratio of 25 percent at Railroad and 15 percent at Mainline. Comparison is difficult as the feed rate per inch of pipe diameter is higher at the Mainline Station while the volumetric air to water ratio is lower. This dilemma is resolved by consideration of the amount of oxygen applied. At the Railroad Station this was equivalent to 60 mg/l. At the Mainline Station with a constant air feed and variable sewage flow the oxygen applied ranged from 36 to 67 mg/l. On this basis the data obtained would indicate compatible oxygen requirements for the control of sulfides in raw sewage independent of other parameters. There are insufficient data over a sufficiently broad range to substantiate the use of applied oxygen at a uniform rate; however the potential should be recognized as it would provide a better design parameter for sulfide control than for air feed rates expressed as a function of pipe diameter.

PRESSURE TANKS

There were two pressure tank aeration devices designed for the project to be used at locations with short force mains. These were installed at the Nineteenth Street-Stillwell Boulevard Lift Station and at the site of the former Pear Ridge Sewage Treatment Plant. The former had a force main of 600 feet and the latter approximately 100 feet. The major problem at these locations was the high sulfides arriving at the wet well and not sulfide generation in the short force main.

The pressure tank proved to be effective in the oxidation of the existing sulfides and the entrainment of air in the sewage. The volumetric air to water ratio of this aeration device was 391 percent at nominal conditions, representing an oxygen application of 949 mg/l. The nominal retention time of the sewage in the pressure tank was 17 minutes at design conditions.

One of the problems that developed during the operation of this aeration device was the build-up of solids in the tank. The solids that collected in the bottom of the tank were found to affect circulation patterns thereby reducing oxygen transfer. To eliminate this problem, the drain line was opened and permitted to flow continuously as a return flow to the wet well. The oxygen content of this return flow was found to be effective in the oxidation of sulfides entering the wet well. This solved one of the problems encountered throughout the study and that was the problem of the control of sulfides in wet wells and minimizing corrosion.

There exists an additional problem associated with the pressure tank aeration device as designed and utilized in the project. The operation of the pump to the pressure tank was continuous and designed to handle the average flow through the station. This means that the peak flow will bypass the unit without receiving treatment. This will not present a serious problem if the peak sulfide levels do not occur simultaneously with the peak sewage flows.

It was anticipated in the system design that the residence time in the pressure tank in conjunction with the excess air would result in a BOD reduction thereby adding to the benefits of this device. Further, the retention time in the pressure tank coupled with the recirculation offered the potential for the development or initiating the growth of a biological floc, a necessary condition for a BOD reduction. This was evaluated by performing BOD tests on both filtered and unfiltered samples taken from various sampling points. Suspended solids determinations were also made.

Data collected during a continuous twenty hour sampling period yielded changes in the two primary parameters as anticipated. Suspended solids increased an average of 41 percent whereas the BOD was decreased by an average of 6 and 11 percent for unfiltered and filtered samples. Although a BOD reduction was demonstrated it was not of significant magnitude to be reliable for predictions. The data collected for this system would have been more significant provided the actual flows and recirculation rate could have been quantified. In the absence of flow rates and retention times it is impossible to differentiate between oxygen applied and utilized in the pressure tank and wet well.

U-TUBE AERATION DEVICES

U-Tube aerators were installed at two locations using compressed air and pure oxygen in lieu of aspiration devices. The compressed air application was effective in reducing sulfide levels but was not capable of complete oxidation at the air:water ratios studied. Additionally, the device was effective in the transfer of oxygen which served to oxidize the sulfides in the downstream gravity sewer. The use of gaseous oxygen did achieve high levels of sulfide reduction and the oxygen transfer was below design levels. The dissolved oxygen residual increased with oxygen application rates; however saturation was never obtained.

The hydraulic performance of the U-Tube aeration devices demonstrated that these can be used without excessive energy losses across the system. Considering these losses and the level of oxygen transfer, the U-Tube proved itself to be an effective method in the role of sulfide control. The failure of the pure oxygen to obtain a higher degree of control was a function of improper information on the system hydraulics used in the design of the U-Tube.

SECTION VIII

SUMMARY OF SULFIDE CONTROL METHODS

The objectives of the study were to demonstrate the effectiveness of oxygen in the control of sulfides and to evaluate various means of entrainment. These objectives were achieved with minor exceptions. The scope of the study was of such magnitude that quantifiable results were not always obtainable, particularly with the constraints imposed by the system configuration and operation. The major purpose of the study was to reduce the sulfides and not to study the efficiency of oxygen transfer; however, the ability to control sulfides is related to oxygen transfer.

The information developed is limited to applications where energy is imparted to the sewage by mechanical pumps. In the study the sewage was either lifted or lifted and pumped to a distant point in the sewerage system. The evaluation will first consider air or oxygen injection into force mains followed by U-Tubes and pressure tanks.

Injection

The first consideration is the application of the expanded diffuser sections as shown in Figures 4 and 5 as compared to the use of a straight tap for air or oxygen injection. The installation at the Railroad Station where diffusers were installed will be compared with the straight injection at the Mainline Station using air injection. Information pertinent to the study is given below.

Station	Pump Capacity gpm	Force Main Diameter (in.)	Length	Detention Time
Railroad Ave.- Thomas Blvd.	1200	16	3850	33.4
Mainline (Lakeview)	3000-5500	30	4040	53.9

1- variable speed pump

The Railroad Station required 2.5 cfm-per-inch diameter to control sulfides as compared to a value of 3.7 at the Mainline Station. The volumetric air to water ratios were 24.9 as compared to 14.8 to 27.4 percent. The applied oxygen concentrations on a weight basis were 69.6 at Railroad as compared with 45.9 to 76.6 at Mainline. The air to water ratios and applied oxygen for these installations are very close with air feed as a function of pipe diameter having the greatest variation. There are several observations relative to these values that should be made. The diffusers at the Railroad Station, although not appearing to restrict flow, could have had their performance restricted by rags accumulating on the piping or the diffusers. It was not possible to determine an optimum air feed at Mainline due to the variable speed pumps. For the air feed and range of sewage pumping rates it was only possible to ascertain that the sulfide levels were reduced to acceptable levels and that odors that were common prior to the aeration failed to be observed during the test program. These data are shown in Table 21.

The analysis of the data under these prescribed conditions fail to establish a significant advantage for either the diffusers or the straight tap for air injection. In the absence of more detailed data for specific conditions it does not appear that the expense incurred with the diffusers and the potential maintenance problem are warranted.

The Railroad Station provided the opportunity to evaluate air and oxygen gas under similar conditions with the noted variations in sewage flow. During the periods of optimization, the average BOD and sulfide values were approximately the same. Under the conditions of the testing and at the minimum sulfide levels in the force main discharge, a concentration of pure oxygen of 16.5 mg/l was required to control sulfides compared to an equivalent oxygen concentration from the applied air of 69.6 mg/l. The oxygen from the air was 4.3 times the amount of pure oxygen gas required to effectuate control.

The remaining stations where pure oxygen was injected into the force main required significantly greater magnitudes of oxygen than that found at the Railroad Station. In each instance it was not possible to optimize the oxygen feed and the values reported in Table 21 for the Grannis Station and for the Smith-Young Station are for the best conditions found. The sulfide levels at Grannis were at acceptable levels for the oxygen application indicated, however this oxygen feed would be expected to be excessive. Sulfide levels in the discharge from the Smith-Young Station were reduced, but not to acceptable levels. The levels at the mid-point were acceptable. However, the sulfides were regenerated in the remaining portion.

U-Tubes

The two U-Tube installations enabled comparisons of their performance using compressed air and oxygen. It was not possible to optimize these aeration devices due either to equipment restrictions or design based on erroneous hydraulic characteristics. The information provided in Table 21 is based upon projected performance from the data obtained for the conditions of design without the described limitations. It is significant to note that oxygen required from air is 4.5 times greater than when using oxygen gas. This compares to a 4.2 ratio found for force mains. A further observation is that the applied pure oxygen for the Pioneer Park U-Tube is very similar to that found for the Railroad force main. The volumetric air to water ratios were also found to be similar for compressed air at the Pioneer Park U-Tube and the Railroad Avenue force main.

Table 21

Oxygen Requirements for Sulfide Control

Application	Station	Applied O_2 (Oxygen gas) mg/l	Applied O_2 (Air) mg/l	Air or Oxygen to Water Volumetric Ratio Percent	Air or Oxygen Feed per inch diameter cfm/in. dia.
Force Main – Oxygen	Grannis	82.9	–	6.2	0.625
	Railroad	16.5	–	1.25	0.125
	Smith-Young	56.9	–	4.27	0.250
Force Main – Air	Railroad	–	69.6	24.9	2.5
	Mainline	–	45.9 – 76.6 *	14.8 – 27.4	3.7
Pressure Tank – Air	Stillwell	–	1093	391.3	N.A.
	Pear Ridge	–	964	345.2	N.A.
U-Tube – Oxygen	Lake Charles	13.2	–	2.0	N.A.
Air	Pioneer Park	–	59.7	21.4	N.A.

* constant air with variable pumping rate

Pressure Tanks

The two pressure tanks were very similar in their design and the operation of these aeration devices produced very similar operating characteristics. The requirements for sulfide control were very similar in that the sewage arriving at the wet well had a rather high sulfide level resulting from a rather extensive gravity system.

The flow through these aeration devices was continuous resulting in a continuous operation of both pumps and blowers. It was not possible to optimize the air requirements at these installations due to the configuration and operational requirements.

The volumetric air to water ratios for the two installations was in excess of 300 percent resulting in an applied oxygen equivalent of 964 and 1093 mg/l for the Pear Ridge and Stillwell pressure tanks. These values are excessive when compared with the other methods of sulfide control utilized in the study.

SECTION XI

ECONOMIC ANALYSIS

The control of sulfides was demonstrated using alternate sources of oxygen and variable methods of entrainment. A major factor in the decision to enter into a sulfide control program is that of economics. An economic evaluation of sulfide control must include the cost of alternatives, with the alternatives being different for a new system than for an existing system. This study was conducted on an existing system with results applicable to a new system.

The alternative to sulfide control for a new system will be the use of inert materials in the sewerage system. This eliminates the corrosion problem but will fail to abate other associated problems such as odors. The difference in cost between inert materials and materials susceptible to corrosion can be applied to the cost of sulfide control where the extra benefit of odor control is derived. In the case of an existing system, the alternative to implementing a control program will be replacement, where the structural integrity of the system has not reached a critical point with failure being imminent, the cost for replacement can be applied to a sulfide control program to preserve the system. It is therefore important to be able to evaluate the economics of the alternatives of sulfide control. This constituted a principal component of the study.

The economic evaluation of alternative methods of sulfide control is contingent upon the ability to optimize each method. There are two objectives that could be met when using oxygen for control. First, the control of sulfides independent of oxygen residuals and second, the control of sulfides with a resulting dissolved oxygen residual. In the latter case the goal would be to assure aerobic conditions downstream from the point of control. The constraints imposed by the system studied negated the ability to evaluate the second objective of maintenance of a dissolved oxygen residual. This was attributable to the accumulation of debris in downstream gravity sewers which had a high oxygen demand in the principle interceptors. The system optimizations and economic considerations are therefore based upon sulfide control.

An economic evaluation of sulfide control should include the cost of alternatives for it to serve as a quantitative aid in decision making. It was beyond the scope of the study to make a comprehensive evaluation and the analysis developed is restricted to the sulfide control component. The principle components to be included are source of oxygen, air or pure oxygen, and the method of entrainment. The methods of entrainment are injection into force mains, pressure tanks, and U-Tubes. These are evaluated as to their applications at sewage transfer stations where a force main is involved and where only a lift occurs.

The principle components of the cost of sulfide control equipment are construction, equipment, operation, maintenance and replacement. The magnitude of cost associated with each component can be expected to vary over a large range and will be contingent upon existing facilities and station configuration. A general discussion relative to oxygen source and entrainment equipment will provide the basis for additional analysis.

Initially oxygen was delivered to the station in trailers which were rented from the supplier. This was an economical approach to preliminary investigations but prohibitive for long term operation. If oxygen gas is to be considered for sulfide control, it is recommended that this equipment be installed at the site to determine oxygen requirements prior to the design of a permanent installation. Cryogenic tanks and converters were installed at locations scheduled to use oxygen gas for extended periods. A special concrete foundation was required at one site whereas at other locations it was possible to install the equipment in either the dry or wet pit of the sewage transfer station. There are two alternate sources that should be considered that can potentially reduce the unit cost of oxygen. In some instances it would be possible to pipe gaseous oxygen to the site provided a plant is nearby and an existing easement available. If oxygen requirements are of sufficient magnitude, consideration should be given to the installation of a small oxygen plant. The major costs associated with the use of oxygen gas is the cost of oxygen. Operation and maintenance costs are minimal when using gaseous oxygen.

Air injection by blowers or compressors can usually be installed on existing concrete structures; however, if space is not available, a small concrete foundation will suffice. Consideration should be given to installing the blowers in the dry pit where space is available. The use of blowers requires a higher degree of maintenance than oxygen facilities and the principle operating cost is power. The cost of operation can be significantly reduced by operating only during pumping cycles. Other cost factors include replacement of both blower and motor and the use of silencers on the intake and discharge to reduce noise levels.

The use of elaborate diffusion equipment for either air or oxygen in force mains did not produce any significant benefit when considering the cost of installation and periodic maintenance that would be required.

The U-Tube as a means of oxygen entrainment in sewage can be used either with aspirators, compressed air or oxygen injection. Of these, only compressed air and oxygen gas were evaluated. The costs associated with compressed air and oxygen have been discussed in general terms. The operation and maintenance of the U-Tube itself is negligible as there are no moving parts and the only upkeep required would be periodic painting. The capital cost will be a function of where they are installed. In this study the costs to be given are for the installation of the U-Tube inside the dry pit. Other points where the device could be installed are outside the transfer station or at the end of force mains. A principal advantage of using venturi aspirators is the elimination of operation and maintanance costs associated with compressors.

The pressure tank as an aeration device requires a larger area outside the station than other types of aeration devices. The design of this device requires a continuous operation of both sewage pumps and air compressors thereby increasing power and operation costs. The continuous operation also requires more maintenance than the other aeration methods evaluated.

All costs incurred in the study will not be reported as they would not be representative of an operating facility. Foremost of these that would not be applicable are operating and maintenance costs. The cost for maintenance has been eliminated; however, the cost to be reported for operation is based upon optimum conditions for air and oxygen feeds as determined from the study. The capital cost for each facility is given as well as power or oxygen cost.

Cost comparisons for the various aeration facilities are given in Table 22. Amortized capital cost is based upon an interest rate of 6 percent and an expected life of 30 years. The total annual cost is given and this in turn is given as a cost per million gallons treated, per pound of oxygen applied and per pound of oxygen transferred.

The most favorable aeration facilities for sulfide control, excluding maintenance costs, can be categorized for sewage transfer facilities where a lift only is involved and where a force main is required. For a station where a lift only is required, the most favorable cost found was for a U-Tube using compressed air followed by a U-Tube using oxygen gas. The most favorable cost for force main installations was air injection into force mains followed by oxygen gas injection. These proved to have a lower cost than the U-Tube, which could also be used in conjuction with a force main. The cost of a U-Tube in conjunction with a force main could be reduced by use of an aspirator in lieu of compressed air or oxygen gas thereby reducing the operating cost which was significant. The pressure tank resulted in the highest annual cost and the cost per pound of oxygen transferred. In each instance the cost reported should be considered with the previous discussions presented for each type of equipment.

Table 22

Cost Comparisons for Hydrogen Sulfide Control

Application	Station	Capital Cost $	Amortized Capital Cost $	Annual Operating Cost (Power or Oxygen) $	Total Annual Cost $	Cost/Million Gallons treated $/MG	Cost/lb. O_2 Applied ¢/lb. O_2	Cost/lb. O_2 used &/or transferred ¢/lb. O_2
Force Main	Grannis	3,554.00	258.20	2,495.20	2,753.40	17.46	3.06	2.8
Oxygen	Railroad	3,554.00	258.20	1,080.00	1,338.20	4.24	3.22	3.44
Injection	Smith-Young	3,554.00	258.20	1,080.00	1,338.00	14.55	3.07	3.41
Force Main	Railroad	2,187.15	227.90	678.24	906.14	2.87	0.49	1.98
Air Injection	Mainline	2,187.15	227.90	2,875.56	3,103.46	1.96	0.31	1.29
Pressure Tank	Stillwell	12,500.00	908.13	3,713.40	4,621.53	27.05	0.30	14.51
	Pear Ridge	12,500.00	908.13	2,875.56	3,783.69	22.15	0.28	13.48
U-Tube -								
Oxygen	Lake Charles	10,000.00	726.50	575.60	1,302.10	6.60	5.97	6.63
Air	Pioneer Park	8,448.45	613.78	678.24	1,292.02	3.51	0.71	4.21

SECTION XIII

References

1 Holtzclaw, Leon V., Personal Interview, March 24, 1970.

2 Neel, Marvin, Report to City Council, August 29, 1967.

3 Holtzclaw, Leon V., Report to City Council, August 24, 1967.

4 Nebergall, W.G., F.C. Schmidt, and H.F. Holtzclaw, Jr., College Chemistry, D.C. Heath and Company, Boston, (1963) 2nd Edition.

5 "Safety in Wastewater Works" Manual of Practice No. 1, Water Pollution Control Federation, Washington, D.C. 1959.

6 Santry, I.W., "Hydrogen Sulfide in Sewers" JWPCF, 35, 12 (1580) December 1963.

7 ASCE Manual of Practice No. 37, Design and Construction of Sanitary and Storm Sewers 1969 Rev. Ed.

8 McKinney, Ross E., Microbiology for Sanitary Engineers, McGraw Hill Book Company, Inc. 1962 (p. 100).

9 Pomeroy, R.D., and F.D. Bowlus, "Progress Report on Sulfide Control Research," Sewage Works Journal Vol. 18, 1597 (1949)

10 Neel, Marvin, Report to Water and Sewage Study Committee, Nov. 18, 1968.

11 Heukelekian, H. and Ruby Lassen, "Oxidation of Reduced Sulfur Compounds in Sewage," Sewage Works Journal Vol. 19, No. 6, p. 989 (Nov. 1947).

12 Elder, A.L. and A.M. Buswell, "Changes of Sulfur Compounds During Sewage Treatment", Ind. and Eng. Chemistry, 21, 560 (1929)

13 Parker, C.D., "Mechanics of Corrosion of Concrete Sewers by Hydrogen Sulfide," Sewage and Industrial Wastes Vol. 23, No. 12, 1477 (Dec. 1951).

14 Noller, Carl R., Structure and Properties of Organic Compounds, W.B. Saunders Company, Philadelphia (1962).

15 Eliassen, R., A.N. Heller and G. Kisch, "The Effect of Chlorinated Hydrocarbons on Hydrogen Sulfide Production," Sewage Works Journal, 21, 3, 457 (May, 1949).

16 Baumgartner, W.H., "Effect of Temperature and Seeding on Hydrogen Sulfide Formation in Sewage," Sewage Works Journal 6, 3, 399 (1934).

17 Streeter, H.W., C.T. Wright and R.W. Kehr, "Measurement of Natural Oxidation in Polluted Streams, An Experimental Study of Atmospheric Reaeration Under Stream - Flow Conditions," *Sewage Works Journal*, 8, 2, 282 (1936).

18 Kehr, R.W., "Measures of Natural Oxidation in Polluted Streams, IV. Effect of Sewage on Atmospheric Reaeration Rates Under Stream Flow Conditions," *Sewage Works Journal*, 8, 2, 282 (1936).

19 Parkhurst, J.D., and R.D. Pomeroy, "Oxygen Absorption in Streams," *Journal of the Sanitary Engineering Division*, ASCE, Vol. 98, No. SA 1, Proc. Paper 8701, Feb., 1972, pp. 101-124.

20 Pomeroy, Richard, "Generation and Control of Sulfide in Filled Pipes," *Sewage and Industrial Wastes*, Vol. 31, No. 9, 1082 (Sept. 1959).

21 Pomeroy, Richard, "Sanitary Sewer Design for Hydrogen Sulfide Control," *Public Works*, pp. 93-96 & 130, October, 1970.

22 Davy, W.I., "Influence of Velocity on Sulfide Generation In Sewers," *Sewage and Industrial Wastes*, Vol. 22, 1132,(Sept. 1950)

23 Sewell, R. Joe, and R. H. White, "Progress in Controlling H_2S Corrosion in the Southwest," presented at the 42nd Annual Conference of the Water Pollution Control Federation, Dallas, Texas, Oct. 8, 1969.

24 American Public Health Association, Inc., *Standard Methods for the Examination of Water and Wastewater*, 1965.

25 Pomeroy, Richard, "Hydrogen Sulfide in Sewage," *Sewage Works Journal*, Vol. 13, No. 3, 498 (May 1941).

26 Heukelekian, H., "Some Bacteriological Aspects of Hydrogen Sulfide Production from Sewage," *Sewage Works Journal*, Vol 20, No. 3, 490 (May, 1948)

27 McKinney, R.E., "The Role of Chemically Combined Oxygen in Biological Systems," *Journal, Sanitary Engineering Division*, ASCE, 82, SA 4, 1053 (August, 1956)

28 Pomeroy, R.D., "Flow Velocities in Small Sewers," *Journal W.P.C.F.*, 39, 9 Sept., 1967, pp. 1525-1548.

29 Pomeroy, Richard, "The Determination of Sulfides in Sewage and in Sewer Atmospheres," Sewage Works Journal, 13, 3, 502 (1941).

30 Wisely, W.H., "Experiences in Odor Control," *Sewage Works Journal*, Vol. 13, No. 6, 1230 (November, 1941).

31 Wisely, W.H., "More Experiences in Odor Control," Sewage Works Journal, Vol. 13, No. 6, 1230 (November, 1941).

32 Nelson, Myron K., "Sulfide Odor Control," Journal W.P.C.F., Vol. 35, No. 10, 1255 (October, 1963).

33 Choppin, A.R., and Faulkenberry, L.C., "The Oxidation of Aqueous Sulfide Solutions by Hypochlorites," Journal American Chemical Society, 59, 2203 (1937).

34 Black, A.P., and J.B. Goodson, "The Oxidation of Sulfides by Chlorine in Dilute Aqueous Solutions," Journal AWWA, Vol. 44, No. 4, pp. 309-316, April, 1952.

35 Appel, A.A., "Chemical Treatment of Los Angeles Sewage to Retard Slimes and Sulfides," Sewage Words Journal, Vol. 19, No. 3, 494 (May, 1947).

36 Carpenter, W.T., "Sodium Nitrate Used to Control Nuisances," Water Works and Sewerage, 79, 175 (1932).

37 Heukelekian, H., "Effect of the Addition of Sodium Nitrate to Sewage on Hydrogen Sulfide Production and BOD Reduction," Sewage Works Journal, 15, 2, 255 (1943).

38 Ullrich, A.H., "Forced Draft Ventilation Protects Concrete Sewer Pipe, Controls Odor," Water and Wastes Engineering, April, 1968.

39 Laughlin, James E., "Studies in Force Main Aeration," Journal of the Sanitary Engineering Division, ASCE, 90, SA 6, Preceedings Paper 4150 (December, 1964).

40 Mahlie, W.S., "Removal of Hydrogen Sulfide in Sewage by Aeration," Sewage Works Journal, 7, 1, pp. 91-95 (1935).

41 Chen, K.Y., and J.C. Morris, "Oxidation of Sulfide by O_2: Catalysis and Inhibition," Journal of the Sanitary Engineering Division, ASCE, Vol. 98. SA 1, Proceedings Paper 8710, February, 1972, pp. 215-227.

42 Pomeroy, Richard D., "Cakareous Pipe for Sewers," Journal W.P.C.F., Vol. 41, No. 8, 1941 (Aug., 1969).

43 Texas State Department of Health, Chemical Analyses of Public Water Systems, 1970, Rev.

44 Texas State Department of Health, Design Criteria For Sewerage Systems, Sept. 1968.

45 Personal Correspondence, Robert A. Bowers, P.E., Director of Planning, City of Port Arthur, Texas, March 7, 1968.

46 Sewell, R. J., "Condition of Wet Wells Sanitary Sewage Lift Stations, Port Arthur, Texas," A Report to the Water and Sewer Committee and to the City of Port Arthur, October 24, 1968.

47 Personal Correspondence, Ewin A. Eads, Ph.D., Professor of Chemistry, Lamar State College of Technology, Beaumont, Texas, August 23, 1968.

48 Bruijn, J. and H. Tuinzaad, "The Relationship Between Depth of U-Tubes and the Aeration Process," *J.A.W.W.A.*, 50, 879-883 (1958).

49 Speece, R.E., J.L. Adams, and C.B. Wooldridge, "U-Tube Aeration Operating Characteristics," *Journal of the Sanitary Engineering Division*, ASCE, 95, SA 3, pp. 563-574 (1969).

50 Speece, R.E., and Rudolph Orosco, "Design of U-Tube Aeration Systems," Journal of the Sanitary Engineering Division, ASCE, 96, SA 3, 715, (June, 1970)

51 Mitchel, R.C., "U-Tube Aeration," Environmental Protection Technology Series; EPA 670/2-73-031, September, 1973; U.S. Environmental Protection Agency, Washington, D.C.

52 Condon, R.L., R.A. Cooper, Jr., and A.J. Englande, Jr., "Instream Aeration to Control Dissolved Sulfides in Sanitary Sewers"; EPA 670/2-73-024, July 1973; U.S. Environmental Protection Agency, Washington, D.C.

53 Wrigh[illegible]obert L., "Force Main Aeration Using Gaseous Oxygen," Unpublished Thesis - Lamar State University, June, 1969.

54 Neel, M[illegible]n, "Hydrogen Sulfide Levels in Sanitary Sewerage System," A Report to the City Council, City of Port Arthur, Texas, Nov. 7, 1967.

55 Santry, I.W., Jr., "Sanitary Sewers in Port Arthur, Texas," A Report to the American Concrete Pipe Association, December 1967-March 1968. Presented to the Water and Sewer Study Committee, November, 1968.

56 Bowlus, F.D. and A.P. Banta, "Control of Anaerobic Decomposition in Sewage Transportation," *Water Works and Sewerage*; 79; 11; 369; (1932).